Spatial Scale Perception in Immersive Virtual Reality

Author:
Jingjing Zhang

Senior Supervisor:
Dr. Tham Piumsomboon

Co-Supervisor:
Prof. Rob Lindeman

Associate Supervisor:
Dr. Adrian Clark

Abstract

Virtual Reality (VR) technology can offer users new insights and applications for a wide range of domains, even supporting experiences which are difficult or impossible to achieve in the physical world. One such example is the use of VR to allow users to experience the perspectives of different people in a virtual environment (VE). This particular application promises to be beneficial for disciplines such as architectural and interior design.

In this research, we explore spatial scale perception by simulating different inter-pupillary distances (IPDs) and eye heights (EHs) for the users in VE. The goals of this research are 1) To investigate different levels of manipulation of EH and IPD to provide different spatial scale perception of multiple target groups of users, 2) To provide appropriate perspectives for enabling a suitable estimation of the virtual object scale for the target groups of users, and 3) To utilise different perspectives for assisting the designers in meeting the needs of different target groups of users. To achieve these goals, we developed a multi-scale VR system and conducted a user study, which comprises of two within-subjects design experiments.

The first experiment investigated the relationship between spatial perception and the user's ability to identify and assess risks and hazards in VE. Seventeen participants experienced different perspectives simulating four target groups of users: two-year-old children, eight-year-old children, adults and wheelchair users. This experiment aimed to learn the impacts of different spatial perspectives to assist the user in designing a safer environment for everyone. We found that varying spatial scale perception had significant impacts on the perceived level of risk, the heights of the identified risk, and the number of risks discovered. The results yielded empirical evidence to support that experiencing different spatial scale perception can potentially help identify issues during an architectural design process for various groups of users.

The second experiment examined three levels of spatial scale perception: two-year-old children, eight-year-old children, and adults, in a task to estimate chair scales suitable for different target users. We found that the disparity between the perspective taken and the target user groups had a significant impact on the resulting scale of the chairs, and different levels of EH and IPD had a positive correlation to the scaling outcome. The key contribution of this study is the evidence to support that experiencing different spatial scale perception in VR has the potential to assist in the better interior or furniture design for various end-users.

Publication

A peer-reviewed publication listed below is based on research completed as part of this thesis:

- Jingjing Zhang, Thammathip Piumsomboon, Ze Dong, Xiaoliang Bai, Simon Hoermann, and Rob Lindeman. "Exploring Spatial Scale Perception in Immersive Virtual Reality for Risk Assessment in Interior Design". In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Deputy Vice-Chancellor's Office
Postgraduate Research Office

Co-Authorship Form - Masters

This form is to accompany the submission of any thesis that contains research reported in co-authored work that has been published, accepted for publication, or submitted for publication. A copy of this form should be included for each co-authored work that is included in the thesis. Completed forms should be included at the front (after the thesis abstract) of each copy of the thesis submitted for examination and library deposit.

Please indicate the chapter/section/pages of this thesis that are extracted from co-authored work and provide details of the publication or submission from the extract comes:

We published the follow paper:

- Jingjing Zhang, Thammathip Piumsomboon, Ze Dong, Xiaoliang Bai, Simon Hoermann, and Rob Lindeman. "Exploring Spatial Scale Perception in Immersive Virtual Reality for Risk Assessment in Interior Design". In Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, 2020

These sections share information from the above paper:

- *Chapter 4 User Study, section 4.3 Participants, 4.4 Setup and Procedure and 4.5 Experiment1: Risk Identification & Assessment from page 21 to 27*
- *Chapter 5 Discussion, section 5.1.1 Experiment 1- Risk Identification & Assessment from page 38 to 43*

Please detail the nature and extent (%) of contribution by the candidate:
The candidate has done 85% of the work

Certification by Co-authors:
If there is more than one co-author then a single co-author can sign on behalf of all
The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the Masters candidate's contribution to this co-authored work
- In cases where the candidate was the lead author of the co-authored work he or she wrote the text

Name: *THAMMATHIP PIUMSOMBOON* Signature: *T. Piumsomboon* Date: *9 March 2020*

Acknowledgements

Foremost, I would like to express my sincere gratitude to my senior supervisor Dr Tham Piumsomboon for his guidance and constant support of my Master's study and research, for his expertise, patience, and motivation. Without his help, this thesis would not have been possible. I would like to thank my co-supervisor Prof. Rob Lindeman, and associate supervisor Dr Adrian Clark, for their generous suggestions, support, and insightful comments. I would also like to express my appreciation to staff and students in HIT Lab NZ, for their kind assistance and encouragement. Last but not least, I would like to thank my family and friends for their continuous support, understanding and caring.

Table of Contents

Chapter 1
Introduction

To create better designs, designers must empathise with their target users, who may be physically different from them or have special needs, e.g. young children, users with disabilities. Virtual Reality (VR) has the potential to improve and accelerate the design process by letting the designers and stakeholders experience different designs from many perspectives within virtual environments (VEs). This research focuses on utilising VR for users to experience an alternate perspective in an application for interior design [9], with a focus on health and safety in a household environment, and furniture design, to better understand the design needs for different target groups.

Spatial scale perception is our ability to perceive the relative size between ourselves, objects of interest, and the surrounding environment. These experiences are subjective to each individual, and there are a number of factors that influence one's spatial scale perception, such as eye heights (EHs) and inter-pupillary distances (IPDs). For example, a small child with a lower EH and smaller IPD would perceive the environment to be larger than an average adult [22]. However, designers of children's furniture are typically adults who perceive the world from an adult perspective. This difference in perspective and experience between the designer and the end-user can make the design process challenging, not to mention other shortcomings such as a lack of standardization and safety regulations for children's furniture [19]. Although in the real-world varying eye height is trivial, IPD can be challenging to change dynamically in the real-world. However, these attributes can be trivially altered within VR.

Past research has found that the manipulation of both EH and IPD are crucial to simulate different levels of spatial scale perception, and that altered perception could elicit different behaviour from users [22; 43]. Banakou, Groten and Slater [4] demonstrated a system that lets users experience a child perspective in an immersive VE. They found that altering the user's virtual body representation in VEs influenced their spatial scale perception. Furthermore, the alteration also affected their behaviour as well as their attitude. In their study, it was found that the users illustrated child-like attributes [4] when experiencing a child's perspective of the VE. Similarly, in another study that had the participants experience different virtual representations, one taller and the other shorter, they found that the users experience a taller representation appeared more confident during a negotiation task [56].

Our interest lies in utilising VR to allow users and designers to experience various spatial scales in the disciplines of architectural and interior design. VR has been an important visualisation tool for decades. In early VR research, Zhang and Furnas [58] explored supporting multiple perspectives in multi-scale collaborative virtual environments (MCVEs). Their system allowed users to collaborate in the VE and gave an example of a collaborative urban planning task where the user could view the city from a regular or a giant scale to support structural visualisation.

Interior architecture is a specialised branch of the architectural discipline [9] where furniture design is an essential element in interior design [3; 7]. For interior designers, one of the most crucial considerations when designing products is target users who have special needs and requirements, e.g. children of different ages, users with disabilities. According to Jurng and Hwang [19], there is no standardisation nor regulation on the safety of children's furniture. Therefore, the challenge faced by the designers is to create products for children of different ages from an adult perspective. From previous research, there is strong evidence that VR can offer users multiple spatial scale perspectives, which may also influence their behaviour inside the VE. We believe that VR can be a powerful design tool to assist and influence designers in the creation of safer and more suitable products for different groups of target users.

To the best of our knowledge, few studies have investigated how manipulating spatial scale perception in VR can help improve disciplines such as interior architecture. It is our goal to develop and evaluate a VR system that supports a broader design space, based on the simulating the perspective of target users for the designers. We consider two key independent variables, eye height and IPD, which are determined given the age range of target user groups. In this research, a user study comprised of two experiments was conducted. The first experiment explores four perspectives, varying the user's eye height and IPD to simulate two-year-old children, eight-year-old children, typical adults and wheelchair users, to identify and assess risks in a two-storey apartment in VE. The second experiment has participants scale six virtual chairs in VE to the preferable size for the target user based on the perspectives of a two-year-old, eight-year-old, and an adult. We hypothesise that the manipulation of spatial scale perception of the designers will result in different outcomes of the risks identified in the first experiment, and the estimated spatial scale of virtual chairs in the second.

This work contributes the knowledge and yield the following benefits to both the design and human-computer interaction (HCI) community: 1) better understanding of the effects of spatial scale perception in architectural design, 2) the development of a design tool to assist interior designers in streamlining the design process in VR, 3) to improve the designer's empathy of the target users, which help lower the cost of design overhead, and 4) to support the creation of user-friendly design that is safer and more suitable for the end-users.

In the sections to follow, we cover the background research in Chapter 2 Chapter 3 gives an overview of the system developed for the user study. Chapter 4 provides the experimental details and results of our user study. Finally, the discussion of the findings from both experiments and our conclusion as well as possible future work are presented in Chapter 5 and 6, respectively.

Chapter 2
Background Research

Spatial perception is one of the processes of spatial cognition [37]. Spatial cognition can be defined in a simple term of how people understand space [34]. Spatial perception is the ability to perceive spatial relationships with respect to people. It includes the exteroceptive and interoceptive processes. The exteroceptive processes create the representation of the space through feelings. The interoceptive processes create the representation of the human body, such as its orientation and position [12; 31]. Space is generally understood as everything around us [31]. Spatial perception enables us to understand the environment and our relationship to it and also the relationship between two objects when their position in space changes [31]. Spatial perception allows people the ability to perceive and understand spatial information in surroundings such as features, sizes, shapes, position, and distances [50].

According to Henry and Furness [16], spatial perception consists of three parts: the size and shape of individual spaces, the relative location of the observer in the overall layout and the feeling of individual spaces. The spatial scale perception explored in our study mainly focused on the perception of the size of objects relative to oneself or individual spaces, which is similar to the definition given by Pinet [41] that spatial perception in the design context is defined as people 's understanding of the proportions of a given object or space.

In this chapter, we give our background research related to the proposed research, which has been categorised into five topics including manipulation of spatial scale perception in Section 2.1, multi-scale virtual environments in Section 2.2, unnatural-scaled virtual embodiment in Section 2.3, behaviour modification from different perspectives in Section 2.4, and finally, Section 2.5 discusses the risk assessment and safety in VR.

2.1 Manipulation of Spatial Scale Perception

Several previous studies have investigated the various effects of eye height and interpupillary distance (IPD) on size and depth perception in stereo displays. Using immersive VR, Dixon et al. [10] studied the effect of eye height scaling on absolute size estimation. Participants wore VR headsets and watched themselves standing in a virtual environment composed of flat ground and a cube. Three differently sized cubes placed at two different distances were observed through two different virtual eye heights. They found that when the eye height was lower, the participants felt that a cube was larger, which indicated that the virtual eye height had influenced one's perception of the virtual object's scale.

Leyrer et al. [27] studied the impacts of virtual eye height and self-representing avatar on egocentric distance estimation and the perception of room dimensions. The results showed that eye height influenced egocentric distance perception and room-scale perception. Nevertheless, the self-representing avatar was found to influence the distance judgement only. Best [5] studied how IPD affects the size perception of two-dimensional (2D) objects when using HMDs. The participants had to judge the scale of 2D objects with varying IPD at 50mm, 63mm, and their own IPD. The results were unable to conclude that IPD influenced the judgment of the 2D objects' scale or not. However, it did have impacts on the user's level of comfort. Williamson et al.[54] found no significant difference when comparing the participant's own IPD against 65mm, and no IPD, on the distance estimation of targets in VR. They speculated that IPD would only influence depth perception in close range.

Kim and Interrante [22] investigated how the manipulation of IPD and eye height influenced the user's perception of their own scale. In their study, the participants experienced nine conditions of all the combination of three levels of eye heights and three of IPDs in a virtual environment (VE). The participants were asked to estimate the size of a virtual cube in each condition with rich visual cues. The results showed that manipulating the eye height or IPD alone did not yield a significant impact on the judgment of scale. However, an extreme increase in IPD resulted in a significant decrease in the estimated size of the virtual cube.

Previous work indicates that eye height and IPD do influence the scale estimation of virtual objects. However, few experiments have explored the manipulation of the eye height and IPD to simulate the perspectives of actual target user groups to estimate the scale of the object suitable for themselves or different target groups. In our experiment, the participants interacted with the virtual objects and scaled the objects from different perspectives.

2.2 Multi-Scale Virtual Environments

MCVE or Multi-scale Collaborative Virtual Environments were first introduced by Zhang and Furnas [58]. In this work, MCVEs were used as a multi-scale perspective changing tool for large structure visualisation such as in urban planning. Multiple users could choose their scale preference as a giant or regular human scale and collaborate in the virtual environment (VE). The benefit of using an MCVE was that the users could observe finer details of the structures at a regular scale while having a better understanding of the overall layout as a giant. Le Chénéchal et al. [26] proposed an asymmetric

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

collaboration between multiple users in a multi-scale environment to co-manipulate a virtual object. One of the users could have a perspective of a giant and could control the coarse-grain movement of the object, while another user could have an ant scale and responsible for a finer-grain manipulation. Kopper et al. [23] presented two navigation techniques for multi-scale VEs to help users interact and collaborate at microscopic or macroscopic levels. Fleury et al. [14] introduced a model to deal with a multi-scale collaborative virtual environment, which integrated the user's physical workspace into the VE to improve the awareness of the physical environment of the others as well as their physical activities and limitations. As a result, users could collaborate more effectively by being aware of the interactive capabilities of other collaborators.

In Mixed Reality, Piumsomboon et al. [44] demonstrated an asymmetric collaboration between AR and VR users in a multi-scale reconstruction of the physical environment of the AR user. In this research, the VR user could scale themselves up into a giant and manipulate the larger virtual objects such as furniture or scale down into a miniature to interact with tabletop objects. In another study [45], they proposed Giant-Miniature collaboration (GMC), a multi-scale mixed reality (MR) collaboration between a local AR user (Giant) and a remote VR user (Miniature). They combined a 360-camera with a six degree of freedom tracker to create a tangible interface where the Giant could physically manipulate the Miniature, and the Miniature was immersed in the 360-video provided by the Giant.

Simulating giant perspectives can be helpful for users to grasp the spatial scale of large structures, which is difficult to comprehend at a regular scale. These previous researches inspired us to apply the multi-scale perspective technique to interior architecture. Nevertheless, instead of providing the perspectives of a giant or an ant, we focus on the perspective of real target user groups to explore whether different spatial perspectives can influence the designer in their design tasks.

2.3 Unnatural-Scaled Virtual Embodiment

In terms of one's perception of their body relative to the surrounding, Linkenauger et al. [29] suggested that we could use the dimensions of the body parts and their action capabilities as the "perceptual rulers" to scale the objects in the surrounding accordingly. They investigated the effects of scaling the virtual hands and the perception of graspability of virtual objects. It was found that as the virtual hands were shrunk, the participants perceived that objects got larger. In a follow-up study [28] they explored the impact of virtual arm's reach on perceived distance. They allowed participants to observe the virtual environment from a first-person perspective and introduced illusions to participants by changing the length of the virtual arm.

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

It was found that the participants with longer arms perceived a shorter distance from the target. However, the premise was that the participants had sufficient experience in performing reaching action. In another study, Jun et al. [18] examined the effects of scaling the virtual feet and the judgment of one's action capabilities. They found that as the virtual feet scale decreased, participants estimated a larger span of the gap and felt less able to cross it.

These studies show that the scale of the virtual body affects the user's perception of their surroundings. In our first experiment, we provided a pair of virtual hands, but the appearance was abstract and robot-like, to reduce the potential impact. Furthermore, to reduce the influence of the virtual hand's size on the spatial perception, we scaled the virtual hands according to the current perspective's scale keeping the observed size of the virtual hands remain constant in each condition. In the second experiment, in order to prevent the impact of the size of the virtual hand on the scale estimation of the virtual objects, we replaced the virtual hands with blue spheres of constant size in different condition.

2.4 Behaviour Modification from Different Perspectives

VR enables people to experience different situations from a variety of perspective of the others [2] and extensive research has been conducted to investigate user experience in such area. It was found that once the users gained the experience of being another person, the spatial perception, behaviours, and their attitudes were affected by the new perspective. Banakou et al. [4] studied the impact of changing the self-presenting avatar on perception and behavioural consequences. In their study, the participants experienced two forms of avatars, one with a four-year-old child's body and the other with an adult's body but scaled down to the same height. The participants were asked to estimate the cubes' size and completed an implicit association test. The results showed that when participants experienced the child's body, they tended to overestimate the cube size which led to a faster response time for self-classification with child-like attributes.

In a follow-up study, Tajadura-jiménez et al. [53] conducted a two by two factorial design study between the two avatar similar to the previous experiment but with two additional auditory cues using the participant's real voice and a child-like version. They found that the child-like voice could create an illusion of being a child and influenced the participant's perception of their identity, attitude, and behaviour. Yee and Bailenson [56] studied the influences of the altered self-representation on the behaviour. They observed that participants with more attractive avatars were more intimate with the opposite gender than those with less attractive ones. Moreover, participants with taller avatars were more confident in a negotiation task than those with shorter ones. Nishida et al. [35] created a waist-worn device made up of a

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

stereo camera for the user to view the world from a smaller person's perspective essentially shifting the user's eye height to waist level. In the study, behaviour changes were observed as the participants behaved more like children, while people around them also interacted with the participant differently. They believed that one of the implications of their technique could be used to assist designers in spatial design and product design, to better understand users who were smaller in height.

Other studies allowed users to take the perspective of other groups, such as the elderly [57], children in wheelchairs [46], homeless people [17], and people who experience schizophrenia [39]. Researchers reported that by looking at the others' perspectives, participants could reduce negative stereotypes about certain groups, and could increase empathy and positive perception toward them. Some studies have shown that by assigning participants, different skin colour avatars to induce participants' body ownership illusions. They found that the participants' attitudes toward the target groups that they had experienced were changed, thereby reducing the implicit racial bias and social prejudice [33; 38].

Through these studies, we found that even if users knew that their perspective in the virtual world was not real, their attitudes and behaviour toward inside that world still changed. This is helpful in our experiments, which simulate perspectives of two different age groups of children as well as wheelchair users. We believe that participants would perceive the environment and interact as if they are the target user and be able to share their insights into their experience from the target user point of view.

2.5 Risk Assessment and Safety in VR

There have been researches investigating risk assessment and safety using VR technology. Perlman et al. [40] conducted a study that allowed construction superintendents and civil engineering students to identify hazards and assess the risk level in a typical construction project in two ways. First, they were to review photographs and project documents. Second, by visiting a virtual construction site using a three-sided CAVE or Cave Automatic Virtual Environment, which uses a projection system to project onto the surrounding wall [8]. The results showed that even the experienced construction superintendents could not identify every hazard in their work environment, and those who used VR could correctly identify more dangers than those who could only examine the documents and photos.

Sacks et al. [48] explored the potential of using virtual reality tools to help designers and builders engage in collaborative dialogues such that the construction projects can be performed more securely. During the test, participants used a CAVE to review the proposed designs and to examine various alternative designs and construction options. They found that the

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

primary advantage of using a CAVE was that the users could identify potential dangers without risking their own safety. The results showed that through conversations and presentations in VR, various security issues became more apparent.

Hadikusumo and Rowlinson combined VR with a design-for-safety-process database to create the DFSP tool [15], which supports visualisation of the construction process and assists in identifying potential safety hazards that are generated during the design phase and potentially be inherited into the construction phase. The studies with DFSP on the detection and assessment of risks in construction scenarios showed that VR is an effective means to better expose potential risks in such scenarios. These research have demonstrated using VR in a professional setting, especially for construction scenario. Nevertheless, we mainly focus on the scenario in a household setting and assess the risks in the environment by experiencing target users' perspectives.

2.6 Research Questions and Goal

Our research interest lies in applying VR technology to enhance the design process for architects, interior or product designers using immersive architectural and interior design applications. Through two informal interviews with two professional architects, we have identified potential problems that VR technology could address. The first challenge is to help the user understand the spatial perception of the architecture or furniture relative to oneself. This is a relatively common problem when managing the design and construction of structures, especially large ones which are difficult to conceptualise. The second challenge is being able to understand another person's spatial perception of the design, e.g. seeing through the eyes of a child, an elderly, a person in a wheelchair, or someone who is shorter or taller.

From the literature review covered in this chapter, we have learned that past researches have demonstrated systems that support a multi-scale user perspective. They have the potential to improve spatial understanding [58], enhance navigation [1; 24; 43], and enrich collaboration [42; 44; 58]. Beyond manipulating the user's perspective, several studies investigated the effects of altering the scale of the virtual avatar's body parts such as hands [29; 36], feet [18], and self-avatar [4]. They found significant effects on the user's perception for different sizes. In addition, changing perspectives in VR also can help people better understand the other user groups [17; 39; 46; 57]. Techniques such as spatial scale manipulation allow users to view the world from different perspectives. Applying such a technique in a design context has the potential to help designers see the world from the target user's point of view, which might be invaluable during the design process.

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

We hypothesise that by experiencing different perspectives, designers would have a better understanding and be able to empathise with the target users. Therefore the designers would be able to create a better design that is suitable for the target user groups. The primary goal of this thesis is to establish a preliminary study for evidence to validate our belief.

The primary goal in this research is to explore the effects of manipulating spatial scale perception to improve user's spatial understanding through different perspectives in a virtual environment (VE) in the domain of architectural interior design and furniture product design. To achieve this goal, we have raised the following research questions that we intend to answer in this research.

RQ1 – Can different levels of manipulation of eye height (EH) and interpupillary distance (IPD) be able to alter one's spatial scale perception to simulate different target groups of users?

RQ2 – Can different spatial perspectives influence one's spatial understanding and scale estimation in design related tasks?

RQ3 – Would the experience of different perspectives influence the design decision of the designer and satisfy specific design requirements for different target groups of users?

Corresponding to the three research questions, we propose three sub-goals of this research as follows:

SG1 – To investigate different levels of manipulation of EH and IPD to provide different spatial scale perception of multiple target groups of users.

SG2 – To provide appropriate perspectives for enabling a suitable estimation of the virtual object scale for the target groups of users.

SG3 – To utilise different perspectives for assisting the designers in meeting the needs of different target groups of users.

To achieve these goals, we developed a multi-scale VR system and conducted a user study, which comprises of two experiments. We will cover our VR system design in Chapter 3 and our user study in Chapter 4.

[1] https://www.vive.com/nz/product/vive-pro-full-kit/

Chapter 3

System Prototype

To fulfil our goals, we developed a VR system that supports multi-scale perspectives in a virtual environment (VE). There were four design requirements for the prototype system to ensure a high-quality experience for the users. The system must:

R1) be able to support dynamic adjustments of the virtual eye height (EH) and the inter-pupillary distance (IPD) of the user.

R2) be efficient to set up and re-calibrate when required.

R3) be able to provide a realistic rendering of the VE.

R4) support standard navigational methods in VE

Following these design requirements, we have chosen a combination of hardware and software, which will be further described in the following subsections.

3.1 Hardware Overview

To fulfil the first two requirements, R1 and R2, we have chosen to use an immersive VR setup to support dynamic adjustments of virtual eye heights and inter-pupillary distances (IPD) and to enable simple setup and re-calibration of the user tracking space. Below is a list of our hardware equipment, and the setup is illustrated in Figure 1.

1) HTC Vive Pro VR system[1]:
    a. VR Headset × 1
    b. Lighthouse Base Stations × 3
    c. VR Controllers × 2
2) A desktop PC with Intel Core i7 @ 4.40GHz, 32 GB of RAM, and NVIDIA GeForce RTX 2080.

Figure 1: HTC Vive pro full Kit[1] (left), hardware setup (right).

3.2 Software Overview

In order to elicit natural user behaviour in VE, it is essential to provide a realistically rendered environment to create an illusion of an environment closest to the real one, which is the third design requirement, R3, for our system. We have chosen to use the Unreal Game Engine (version 4.15) to develop our system on Microsoft Windows 10 and the SteamVR API (version 1.6.10) to interface with the HTC Vive hardware. The Unreal Game Engine is well known for the real-time realistic rendering technology. Figure 2 shows a screen capture of our software development environment.

Finally, the last requirement, R4, is to support an intuitive method for the users to navigate within the VE. However, the chosen method must not break the sense of presence within VR. This is first provided by HTC Vive system itself, which allows users actually to walk in a particular space. The second is to match the navigation actions with the keys of the HTC Vive controller by writing commands in the Unreal Engine.

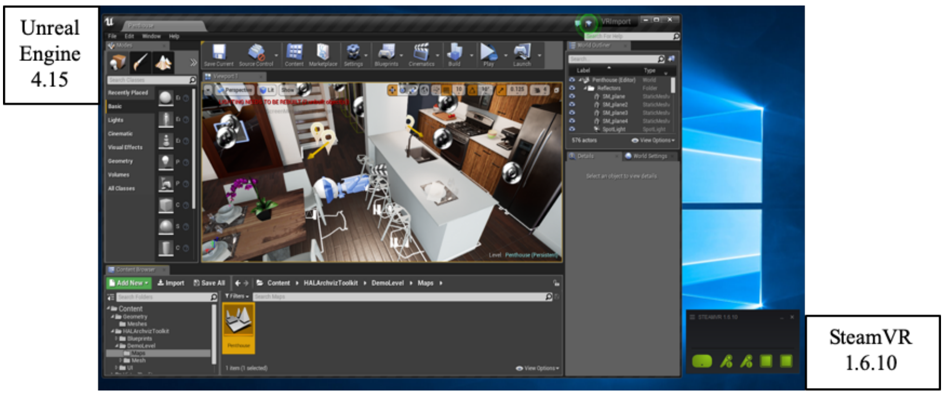

Figure 2: A screenshot of our software environment showing the Unreal Engine and SteamVR interface.

[2] https://docs.unrealengine.com/en-US/BlueprintAPI/Input/HeadMountedDisplay/SetWorldtoMetersScale/index.html

3.3 Interface design

With the combination of hardware and software described in the previous sections, we developed a VR system that supports multiple spatially scaled perspectives that assist users in an application of interior design for two design-related experiments. We further describe the implementation of the VR interfaces in this section. Subsection 3.3.1 explains how we chose various levels of spatial scale perception. The navigation methods used in the experiments are covered in Subsection 3.3.2. The risk assessment tagging and rating process in the first experiment are discussed in Subsection 3.3.3. Finally, Subsection 3.3.4 describes the interaction technique for scaling the virtual chairs in the second experiment.

3.3.1 Manipulation of Spatial Scale Perception

In our VR system, by using the command "Set world to meters scale"[2] and giving the VR camera an offset in the Unreal Engine, we can manipulate the IPD and EH to simulate various perspectives. Taking the process of simulating the perspective of a two-year-old child as an example, according to previous research, we found that the average IPD of a two-year-old child is about 46mm [32; 47]. By referring to the growth chart published by CDC [25], we found the average height of two-year-old boys and girls is about 860mm, and the EH is around 100mm lower than the average height. We took 760mm as the EH to simulate the perspective of a two-year-old child.

In Unreal Engine, the default IPD is 64mm - this value is consistent with the average IPD of an adult, which is around 63mm as reported in previous studies [11; 13]. According to the relationship between the IPD of the simulation perspective and the default IPD, we could change the scale of the virtual world perceived by the user using "Set world to meters scale" command in Unreal Engine. For instance, the IPD of a two-year-old child is about 0.72 times the default IPD, so the virtual world perceived through the simulated two-year-old child perspective is approximately 1.39 times the scale of the virtual world perceives by the adult’s perspective. To simulate a two-year-old child perspective, we would also calibrate the user's virtual EH to 760mm by giving VR camera an offset in the Unreal Engine. Figure 3 shows a simulated two-year-old child’s perspective.

[2] https://docs.unrealengine.com/en-US/BlueprintAPI/Input/HeadMountedDisplay/SetWorldtoMetersScale/index.html

Figure 3: Spatial scale perception - a simulated perspective of a two-year-old child

3.3.2 Navigation Methods in the Virtual Environment

In addition to using the standard navigation methods provided by HTC Vive VR itself, which allows users to walk within a pre-defined area physically. We have also implemented a continuous movement in the system, which enables the user to use the trackpad of the HTC Vive controller to move their virtual representation in a VE. Users could move forward, backward, left, or right by pressing the trackpad up, down, left or, right on the left controller, respectively, as shown in Figure 4. Previous research found that virtual scene movement could cause severe dizziness and nausea [30] and to reduce the cybersickness when using VR, the orientation in the virtual world is controlled by the physical turn by the user's head in the real world instead.

[2] https://docs.unrealengine.com/en-US/BlueprintAPI/Input/HeadMountedDisplay/SetWorldtoMetersScale/index.html

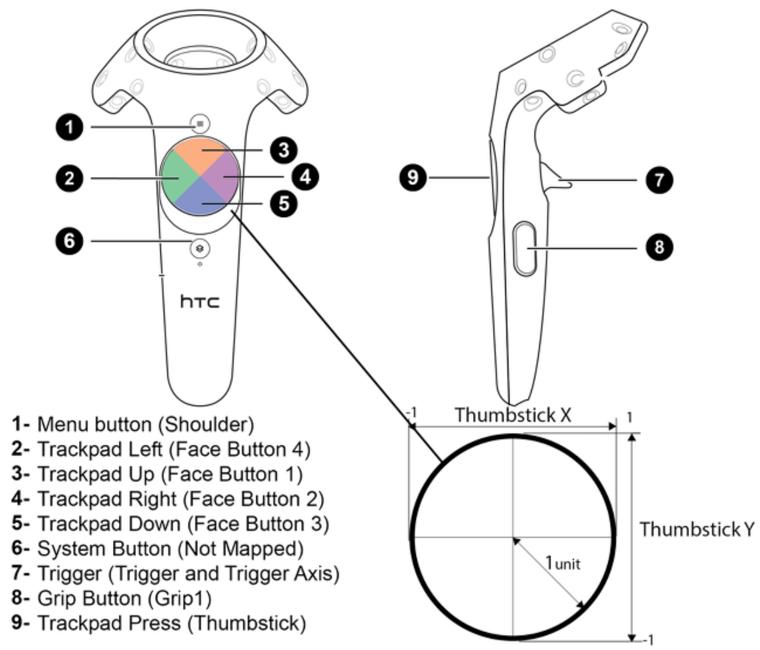

Figure 4: Button mapping names for HTC Vive controller[3].

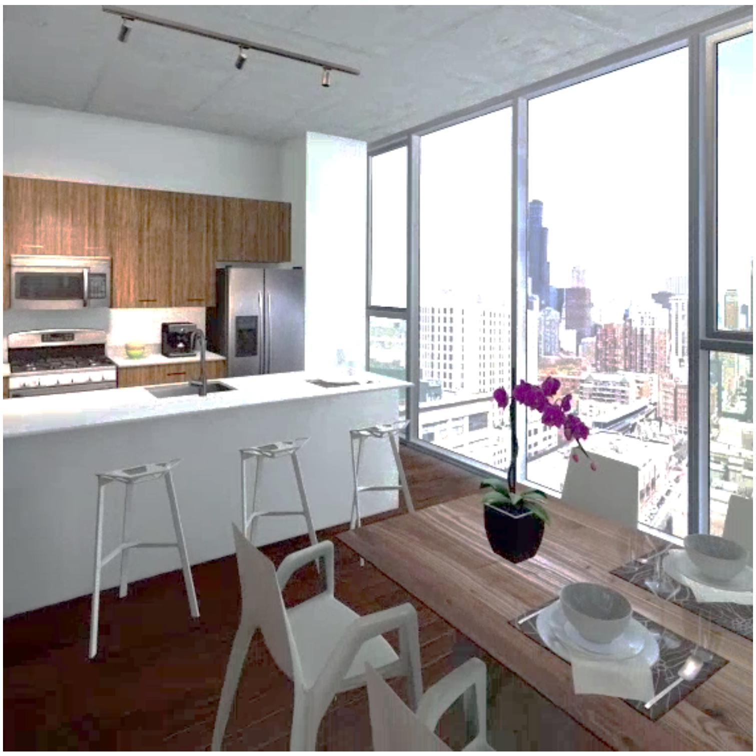

Figure 5: A virtual two-storey apartment used in our system

[3] https://www.criticreviewer.com/htc-vive-now-available-at-lesser-price-in-uae-what-is-htc-vive/htc-vive-controller/

3.3.3 Risk Assessment Tagging and Rating

In Experiment 1 - Risk Identification & Assessment, participants were asked to identify and assess the potential risks in a virtual apartment from different user perspectives. A virtual two-storey apartment used in this experiment is shown in Figure 5. The types of risk presented in the virtual apartment were fires, poisoning, drowning, falls, cuts, and burns [20; 52]. Apart from the inherent risks presented, such as sharp table corners and steep stairs, we included ten randomly positioned risks to reduce the learning effects such as a knife or a flower vase. The height of the randomized position for the same risk was the same across all conditions (see Figure 6). Therefore, the total number of risks in the virtual scene and the heights of the risks appearing in the scene will remain unchanged across conditions.

Figure 6. Randomized places for potential risks.

For the virtual representation in Experiment 1, the participants were given only a pair of virtual hands as we try to eliminate any potential confounding factors such as a self-representation that might influence one's perception beyond the IPD and EH. For tagging and rating the potential risks, our system allows users to:

1) Create a virtual ring to mark the risk by pressing the Grip Button on the left controller.
2) Turn on a ray casting into space by pressing the Grip Button on the right controller.
3) Move the ring marker parallel to the ray being cast to the desired position by pressing the trackpad up or down on the right controller.

4) Change the colour of the ring to assign the level of risk by pressing the Grip Button on the right controller.
5) Delete the unwanted ring marker by using the ray or a virtual hand to select and follow by a Grip Button press on the left controller.

The risk factors were represented by five colours, red, orange, yellow, green, and blue, where red represents the highest risk, and blue, the lowest (see Figure 7).

Figure 7. A user marks a Very High risk while experiencing eight-year-old children's perspective (left), marks a Very Low risk while experiencing adults' perspective (right).

Figure 8 shows the three steps to identify and rate the risks:

1) Tagging: determine the risk or hazard and create a ring to mark it.
2) Moving: the placement position might be further away. Therefore the user needs to move the ring into the correct position using the ray.
3) Rating: to indicate the level of risk on a 5-point Likert scale from very low to very high, the user has to cycle through the appropriate colour for the ring.

Figure 8: The risk assessment marking process

3.3.4 Scaling the Virtual Chairs

In Experiment 2, participants were asked to scale six virtual chairs to a suitable size for the target user groups while experiencing different perspectives in immersive VE. The primary purpose of this task is to explore whether experiencing different perspectives of spatial perception would affect the user's spatial perception and yield different scale estimation. Therefore, we tried to avoid any potential confounding factors, especially the relative body parts compared to the virtual object. We decided to remove the virtual hands used in Experiment 1 and replaced them with two blue spheres to inform the users of their controllers' position. The VE has also been changed from an indoor apartment to an outdoor open space. This was to avoid the relative scale comparison of the chair to the room. Figure 9 shows a user experiencing a two-year-old child perspective while scaling the chair from the default starting size to the preferable size suitable for the current user perspective. The default size of the six virtual chairs was an approximation of the size of the actual physical chair, where the height of the seat was 430 mm from the ground, and the width was around 450 mm.

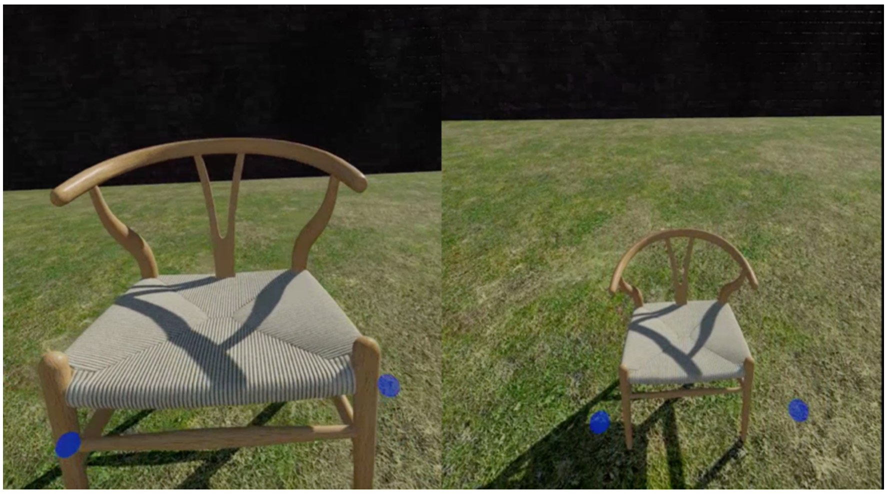

Figure 9: A user scales the chair from the default starting size (left) to a preferable size for two-year-old children (right) while experiencing a two-year-old child's perspective.

To scale the chairs, we implemented an interaction technique, that allows the user to make contacts using the blue spheres, representing the controllers, with the virtual chair. The users then press and hold the trigger button on the controller, then moving their controllers apart to scale the chair up or moving them closer to scale it down, as shown in Figure 10.

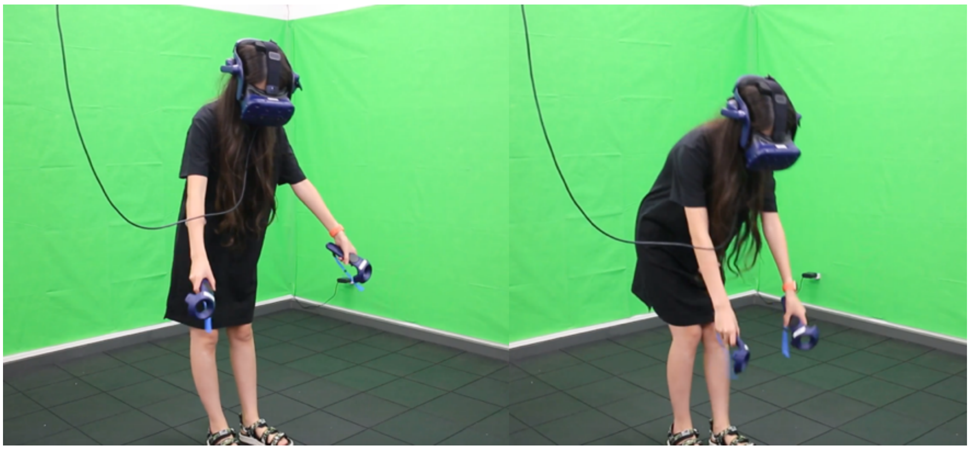

Figure 10: A user is scaling up the virtual chair (left), scaling down the virtual chair (right).

Chapter 4

User Study

In this chapter, we discuss our user study, which consists of two experiments. We briefly discuss the pilot study of our VR system in Section 4.1. We provide details of the methodology, participants, and study design in Section 4.2, 4.3, and 4.4, respectively. In Section 4.5, we present the first experiment of our user study, which examined the effects of experiencing different spatial scale perspectives on the topic of risk identification and assessment in interior design. In the second experiment, we investigated the effects of different spatial scale perspectives on a virtual scale estimation of a furniture design task in Section 4.6. Finally, Section 4.7 covers the measurements of the questionnaires used in the study.

4.1 Pilot Study

We conducted a pilot study with five participants (two male and three female). The pilot study mainly focused on the system setup of Experiment 1 for risk identification, which was more complex than the second experiment. The goal was to test the usability of our VR system. This could help identify any technical issue prior to the formal study. We ran the experiment as we would in the formal study. The participants were given an introduction to the VR system and were briefed on the experiment procedure. The VR controller's operation and the VR interface's features were demonstrated to the participants, which included the navigation technique and the method to tag and assess the risks. The participants were encouraged to think aloud as they familiarised themselves with the system.

Based on the participant's performance in this preliminary test and the feedback given post-experiment, we summarized several areas that could be improved. Firstly, two participants felt that the button mappings of the VR controller were quite complicated for them. We modified those mappings according to the feedback from the participants and tested them again to validate the improvement. Secondly, two participants reported feeling dizziness after using the VR system. We identified that one of the contributors was the continuous movement speed within the VE. To alleviate the issue, we reduced the maximum movement speed of the system. Finally, unrelated to the usability issue, three participants commented that it was not apparent to them of the types of risk that they needed to identify. Therefore, we provided a training session and examples of the types of risk that could be found around the household to the participants in the formal study.

4.2 Methodology

To address the three research questions raised in Subsection 2.6, we designed two experiments, both within-subjects design, to investigate the effects of spatial scale perceptions in design-related tasks. In Experiment 1, the participants had to identify and assess the potential risks in a two-storey virtual apartment from different target user's perspectives. This experiment aimed to answer our first research question, *RQ1*, "Can different levels of manipulation of eye height (EH) and interpupillary distance (IPD) be able to alter one's spatial scale perception to simulate different target groups of users?". Experiment 2 investigated the effects of different spatial perspective on virtual object scale estimation, which aimed to verify the second research question, *RQ2*, "Can different spatial perspectives influence one's spatial understanding and scale estimation in design related tasks?". Subsequently, the outcomes from both experiments should provide sufficient evidence to answer the last research question, *RQ3*, "Would the experience of different perspectives influence the design decision of the designer and satisfy specific design requirements for different target groups of users?". More details of the experimental design will be given in Section 4.5 and 4.6.

4.3 Participants

For the formal study, our ethics application, with a reference number of HEC 2019/93/LR, was submitted and approved by the Human Ethics Committee, the University of Canterbury on the 14th of November 2019. The participants had to sign a consent form, which contained the experiment information and were informed of the potential effects of cybersickness that may be induced by the VR system. They were explicitly told that they could discontinue the experiments at any time without penalty. We provided the participants with a gift voucher for their participation. We recruited 17 participants (9 females) from students and staff at the University of Canterbury with an average age of 32.4 years (SD=11.8), and an average height of 157.8 cm (SD=41.0). Five participants reported having children. In terms of VR experiences, seven participants had no previous VR experience, six used it a few times in a year, two monthly, one weekly, and one daily. All participants participated in both Experiment 1 and 2.

4.4 Setup and Procedure

4.4.1 Experimental Setup

The experimental space was setup using the HTC Vive Lighthouse tracking system for an interaction area with a dimension of 2.7×2.7 sq.m., overlaying with rubber tiles, as shown in Figure 11. The participants performed the tasks in a standing position in every condition except for the wheelchair condition (*W/C*), where the participants were seated on a wheeled office chair in Experiment 1.

Figure 11: Our experimental setup (top), a user in an experimental space (bottom left), and a user sitting on a wheeled offive chair in the *W/C* condition of Experiment 1 (bottom right)

4.4.2 Procedure

Participants were given the information sheet and the consent form. The experimenter then gave an oral introduction to the study. Once the participants signed their consent form, they were asked to fill out a demographic questionnaire. The participants were then given a training session on how to operate the VR system and familiarise themselves with the interfaces and the VR controllers. Furthermore, the training session was taken place in a different VE, which provided examples of the types of risk that the participants would be identifying in the experiment. During the training period, the experimenter also used this opportunity to calibrate the participant's virtual eye height (EH) to offset the participant's height such that every participant experienced the same EH for the same condition in VE.

When the actual experiment began, the participants experienced each condition in a counter-balanced order, more details on Experiment 1 and 2 will be given in the sections to follow. The participants were asked to think aloud during the experimental process for the experimenter to take notes. When Experiment 1 had been completed, the experimenter only then explained the information of Experiment 2 to the participants. As both experiments were completed, the participants were asked to complete the System Usability Scale (SUS) questionnaire [6], the iGroup presence questionnaire (IPQ) [49], and the post-study questionnaire. Each session took approximately 70 minutes to complete.

4.5 Experiment 1: Risk Identification & Assessment

In this experiment, participants were asked to identify and assess the potential risks in the VE of a two-storey virtual apartment from different user's perspectives. We defined *hazards* as situations that pose a threat to health and safety, and *risks* as products of the consequence and probability of a hazardous event. Participants rated the risk based on the perceived risk to their health and safety from their current perspective.

4.5.1 Design of Experiment 1

To simulate various perspectives, we manipulated three levels of eye-heights (EHs) and three levels of inter-pupillary distances (IPDs), as shown in Table 1.

Table 1: Four conditions were chosen from different levels of manipulation of spatial scale perception between EH and IPD

EH IPD	Low (760 mm)	Moderate (1220 mm)	High (1600 mm)
Small (46 mm)	2 year old		
Medium (54 mm)		8 year old	
Large (63 mm)		Wheel Chair (Adult)	Adult

Instead of a 3×3 factorial design between EHs and IPDs, we were interested in the actual perspectives of different user groups and chose four perspectives to simulate: a two-year-old child (*2yo*), an eight-year-old child (*8yo*), an adult in a wheelchair (*W/C*), and an adult (*Adult*). We based our EH selections on the growth chart published by CDC [25]. We used an EH that was approximately 100 mm below the average height between female and male averages. The height at the age of eight years old was taken to be 1280 mm on average, while the height of an adult sitting in a wheelchair was 1350 mm. The average IPD of adults used in previous research was approximately 63 mm [11; 13]. For the child's IPDs, we referred to MacLachlan and Howland [32] because of their large sample size and fine age division. Figure 12 shows the viewpoint from different perspectives. Note that for the *8yo* and *W/C* conditions appeared to have the same EH. However, the effects of different IPD could not be shown in the figure below with 2D images and required a stereoscopic display to better understand the differences.

Figure 12: Spatial scale perception - four perspectives, a two-year-old child (*2yo*), an eight-year-old child (*8yo*), a person in a wheelchair (*W/C*), and an adult (*Adult*).

4.5.2 Hypotheses of Experiment 1

We compared the outcomes of experiencing *four spatial scale perspectives*, our independent variable, on the user's perception of risks and hazards and their ability to identify them in the VE. We measured and compared three dependent variables, risk rating, number of risks, and risk height, which led us to the three hypotheses as follows:

Experiencing different perspectives in VE would significantly impact the participant's perception of risks in terms of:

*H1: Perceived level of risk (**Risk Rating**),*

*H2: Total number of risks identified (**Number of Risks**), and*

*H3: Average risk height found (**Risk Height**)*

The *Risk Rating* was a 5-point Likert scale. The *Risk Height* was recorded in centimetres. The *Number of Risks* was an accumulated number of risks identified by all seventeen participants in each condition.

4.5.3 Results of Experiment 1

The Shapiro-Wilk Test indicated that our data significantly deviated from a normal distribution (*Risk Rating* - W=0.88, p<.0001, *Risk Height* - W=0.90, p<.0001, and *Number of Risks* - W=0.82, p<.0001). The Friedman test yielded a significant difference for Risk Rating ($\chi^2(2)=951.9$, p<.0001), Risk Height ($\chi^2(2)=1866.1$, p<.0001), and Number of Risks ($\chi^2(2)=89.0$, p<.0001).

For post-hoc pairwise comparisons, we used Wilcoxon signed-rank tests with Bonferroni correction (p-value adjusted). For ***Risk Rating***, the pairwise comparisons yielded significant differences for *2yo-Adult* (V=7856.5, p<.0001), *2yo-W/C* (V=9492, p<.0005), *8yo-Adult* (V=8384, p<.0005) and *8yo-W/C* (V=8797, p<.001) (see Figure 13).

For ***Risk Height***, significant differences were found between *2yo-Adult* (V=2569, p<.0001), *2yo-W/C* (V=5677, p<.0001), *2yo-8yo* (V=9709, p<.0001), *8yo-Adult* (V=6860, p<.0005) and *W/C-Adult* (V=12683, p<.0005) (see Figure 14).

Lastly, for ***Number of Risks***, the pairwise comparisons gave significant differences between *2yo-Adult* (V=148, p<.001), *2yo-W/C* (V=105, p=.002), *8yo-Adult* (V=120, p= .008) and *8yo-W/C* (V=138, p= .004) (see Figure 15). There were no significant differences for ***Session Duration*** between conditions (see Figure 16).

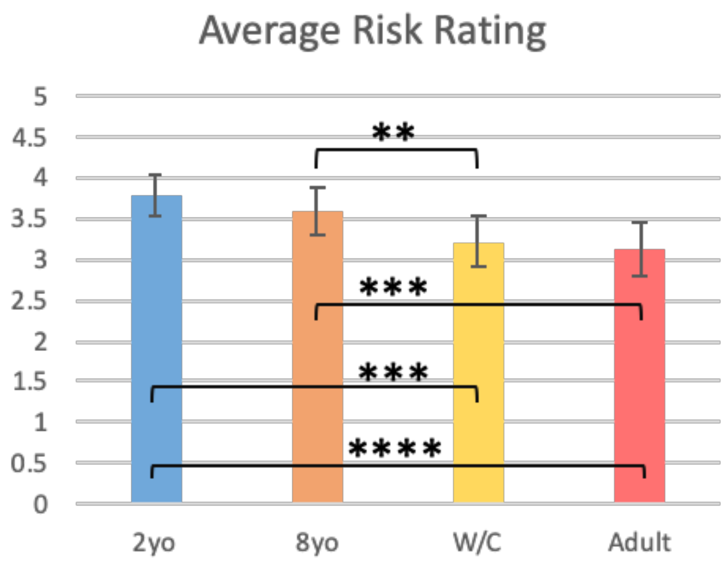

Figure 13: Study results as plots for *Risk Rating* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

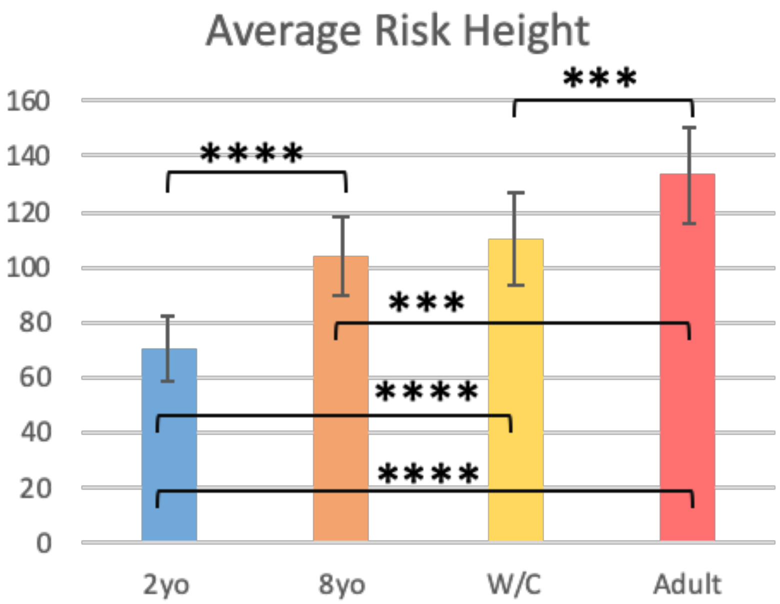

Figure 14: Study results as plots for *Risk Height* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

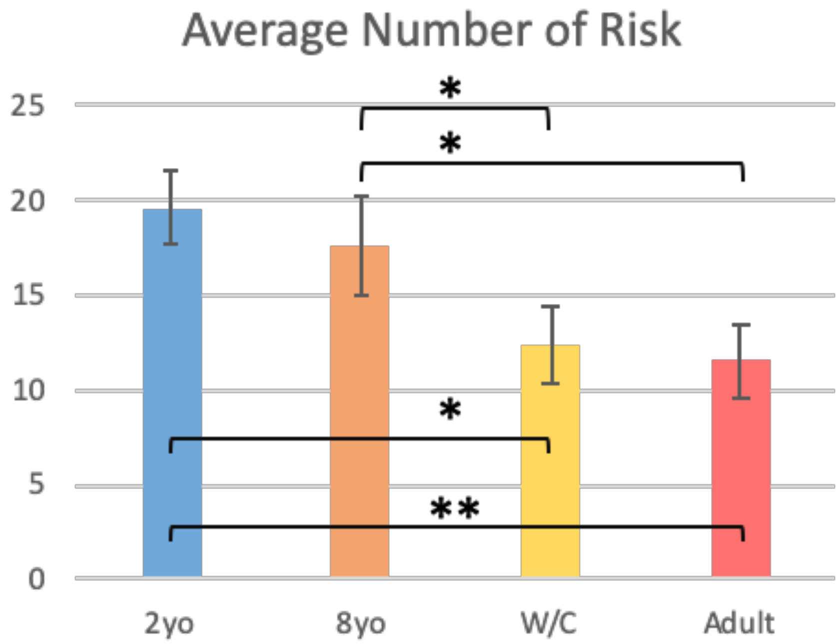

Figure 15: Study results as plots for *Number of Risk* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

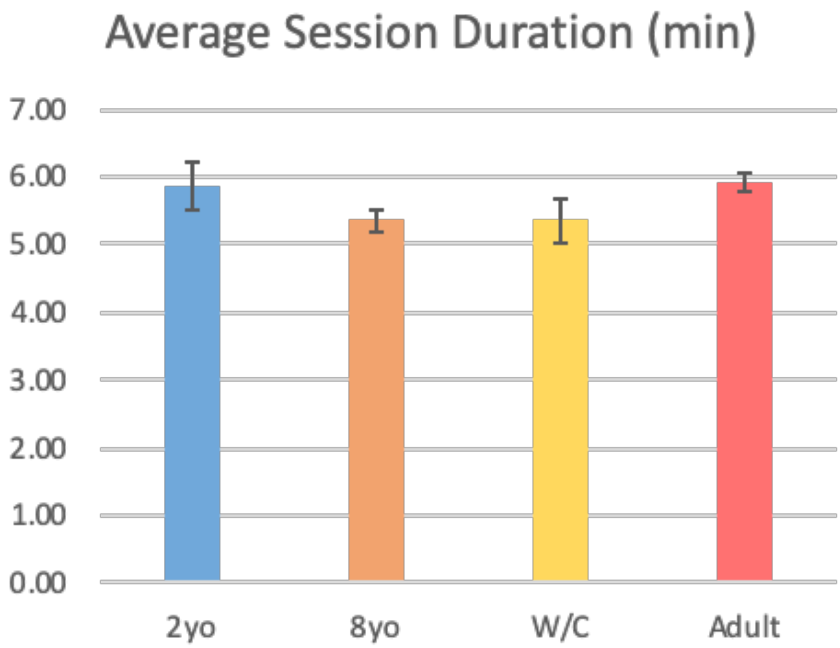

Figure 16: Study results as plots for *Session Duration* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

4.6 Experiment 2: Virtual Design Scale Estimation

We used the three condition from the first experiment for the perspectives of *2yo*, *8yo* and *Adult*. The participants were asked to scale six virtual chairs to the size suitable for the target user groups. For an optimal number of conditions to be compared, we chose to focus on two objectives. Firstly, we were interested in the disparity between the designer's perspective and the product's target user group. Participants experienced two perspectives, *2yo* and *Adult*, where they had to scale the chair for their own age group (*2-2y* and *A-A*) and the other group (*2-A* and *A-2y*). Secondly, we wanted to investigate the impacts of designing from unique perspectives (*2-2y*, *8-8y*, and *A-A*) in terms of IPD and EH on scaling the virtual chair. These two objectives yielded a total of five conditions in this experiment (see Table 2). The first objective will be covered in Part A, *The Impacts of Similarity & Disparity of Perspective in Virtual Design,* and the second one in Part B, *Virtual Design with Different Combinations of IPDs and EHs*.

Table 2: Five conditions in Experiment 2

Perspective Taken \ Target User Groups	2 year old	8 year old	Adult
2 year old (*2yo*)	Scaling for *same* perspective (*2-2y*)		Scaling for *different* perspective (*2-A*)
8 year old (*8yo*)		Scaling for *same* perspective (*8-8y*)	
Adult (*Adult*)	Scaling for *different* perspective (*A-2y*)		Scaling for *same* perspective (*A-A*)

Part A. The Impacts of Similarity & Disparity of Perspective in Virtual Design

4.6.1 Design of Experiment 2 Part A

A 2×2 factorial design was used between our two primary independent variables, the ***Perspective Taken*** (*2yo* or *Adult*) and the ***Target User Disparity.*** The *Target User Disparity* was the matching between the perspective taken and the target user of the scaled chair, which could be either the same perspective as the target (*2-2y* or *A-A*) or different perspective from the target (*2-A*, *A-2y*), yielding four conditions in total for Part A as shown in Table 3.

The only dependent variable (quantitative) was the resulting ***Chair Scale***, which was taken as the ratio of the final chair size and the default size (an adult chair with a scale value of 1.0). In order to better control the effects of the appearance of the chairs on the scaling of the chair, we introduced another independent variable, **the *Chair Type***. Figure 17 shows the six types of chairs that the participants scaled in this experiment.

Figure 18 shows a participant experiencing a *2yo* perspective scaling the virtual chair from the default size to the preferable size for the same target user group as the perspective taken (*2-2y*). Figure 19 also illustrates a 2yo perspective but scaling the virtual chair for an adult instead (*2-A*). Figure 20 demonstrates a user scaling the chair.

Table 3: Four conditions used in Experiment 2 Part A

Target User Disparity / Perspective Taken	Same	Different
2 year old (*2yo*)	*2-2y*	*2-A*
Adult (*Adult*)	*A-A*	*A-2y*

4.6.2 Hypotheses of Experiment 2 Part A

In this part, we focused the comparison on the effects of experiencing different perspectives, the disparity of designing for the same or different target user groups, and for different types of virtual chairs, on the estimated scale of the virtual chair. Our hypotheses were:

*H4: The disparity between the perspective taken and target user's groups (**Target User Disparity**) would have a significant impact on the estimated scale of the virtual chair (**Chair Scale**).*

*H5: The resulting **Chair Scale** would not be significantly impacted by scaling different type of virtual chair (**Chair Type**) for the same condition.*

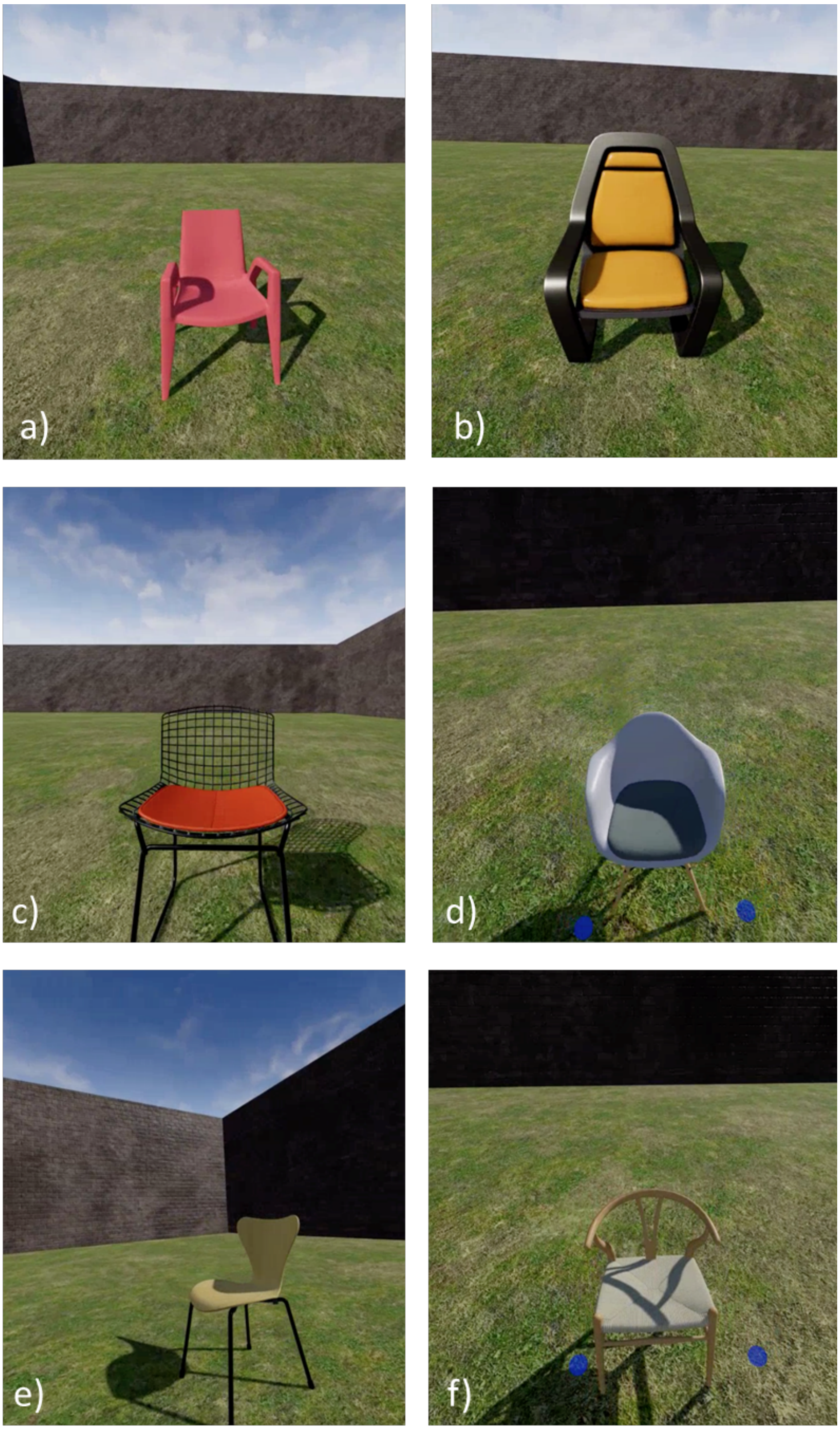

Figure 17: The six types of chairs used in Experiment 2 to better control the impacts of chair design on the scaling task.

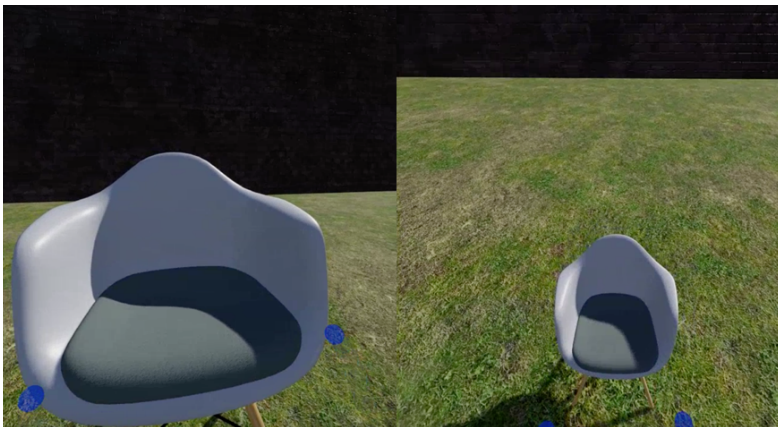

Figure 18: A user scales the chair from the default size (left) to a preferable size for their current perspective (right) while experiencing a two-year-old child perspective.

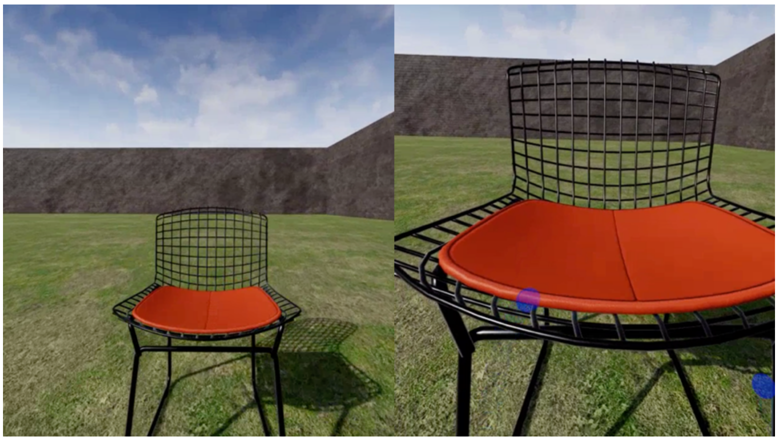

Figure 19: A user scales the chair from the default size (left) to a preferable size for typical adults (right) by experiencing a two-year-old child perspective.

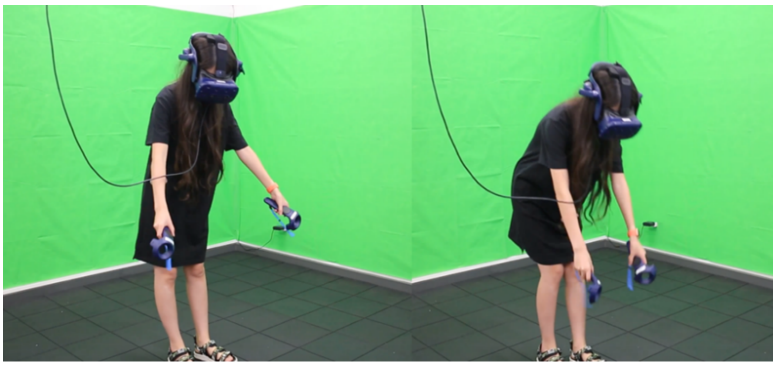

Figure 20: A user was scaling the chair up (left) and down (right)

4.6.3 Results of Experiment 2 Part A

The Shapiro-Wilk Test indicated that our data significantly deviated from a normal distribution (*Chair Scale* - W=0.95, p<.0001). The Aligned Ranks Transformation ANOVA [55] yielded a significant main effect for *Target User Disparity* (F=57.34, *p*<.0001), but no significance was found for *Perspective Taken* and *Chair Types*. There was a significant interaction effect for *Perspective Taken* × *Target User Disparity* (F=1197,19, *p*<.0001), as shown in Figure 21.

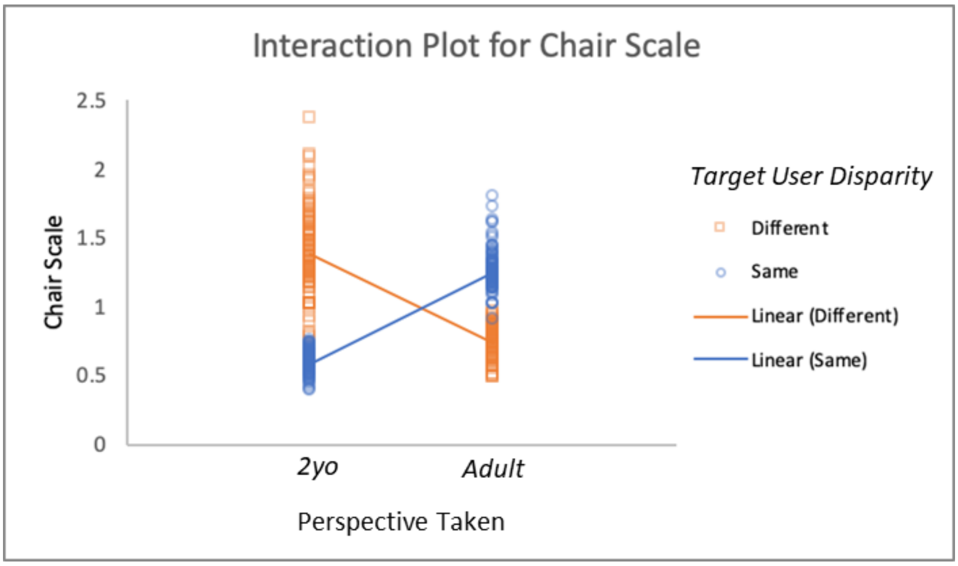

Figure 21: Interaction plot between *Perspective Taken* and *Target User Disparity* for the resulting *Chair Scale.*

For post-hoc pairwise comparisons, we used a Wilcoxon rank-sum test with Bonferroni correction (p-value adjusted). Figure 22 illustrates the plots of the results. For ***Chair Scale***, the pairwise comparisons yielded significant differences between *2-2y* and *A-A* (W=0, p<.0001), *2-2y* and *2-A* (W=0, p<.0001), *2-A and A-A* (W=3260, p<.0005), *2-2y and A-2y* (W=1377, p<.0001), *A-A* and *A-2y* (W=9212, p<.0001), and *2-A* and *A-2y* (W=9075, p<.0001).

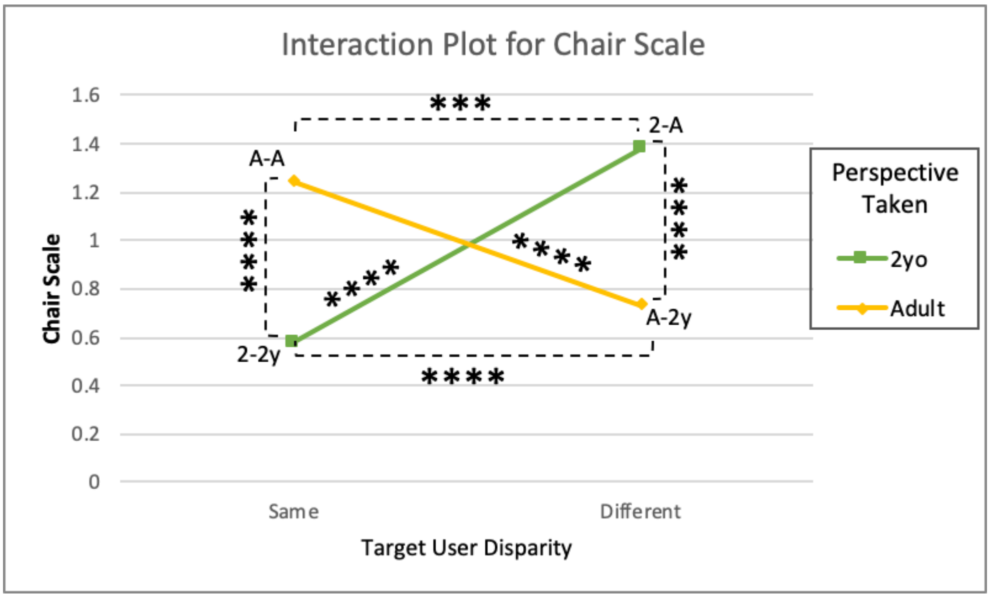

Figure 22: Results of post-hoc pairwise comparisons for *Chair Scale* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

Part B. Virtual Design with Different Combinations of IPDs and EHs

4.6.4 Design of Experiment 2 Part B

In Part B, we used the additional data from the *8yo* condition to compare the impacts and the correlation of different ***Perspective Taken,*** the only independent variable, on the virtual chair scaling task for the same target user group, which yielded the estimated ***Chair Scale***, our dependent variable, for the six types of chairs. We compared three conditions of *2-2y* (EH=760mm; IPD=46mm), *8-8y* (EH=1180mm; IPD=54mm), and *A-A* (EH=1600mm; IPD=63mm) as shown in Table 4.

4.6.5 Hypotheses of Experiment 2 Part B

We compared the effects of different perspectives on the estimated scale of the virtual chair. Our hypotheses were:

> *H6: Experiencing different perspectives (**Perspective Taken**) for a matching target user group would have a significant impact on the resulting scale of the chair (**Chair Scale**).*
>
> *H7: A **positive linear relationship** exists between the eye-height (**EH**) / interpupillary distance (**IPD**), which are the two variables of **Perspective Taken,** with the resulting Chair Scale.*

Table 4: Three conditions used in Experiment 2 Part B

Perspective Taken \ Target User Groups	2 year old	8 year old	Adult
2 year old (*2yo*)	Scaling for *same* perspective (2-2y)		
8 year old (*8yo*)		Scaling for *same* perspective (8-8y)	
Adult (*Adult*)			Scaling for *same* perspective (A-A)

4.6.6 Results of Experiment 2 Part B

We used the Wilcoxon rank-sum test with Bonferroni correction (p-value adjusted) for the pairwise comparisons between *2-2y, 8-8y,* and *A-A*. For ***Chair Scale***, the results yielded significant differences between *2-2y* and *A-A* (W=0, p<.0001), *2-2y* and *8-8y* (W=91, p<.0001), and *A-A and 8-8y* (W=8924, p<.0001) (see Figure 23).

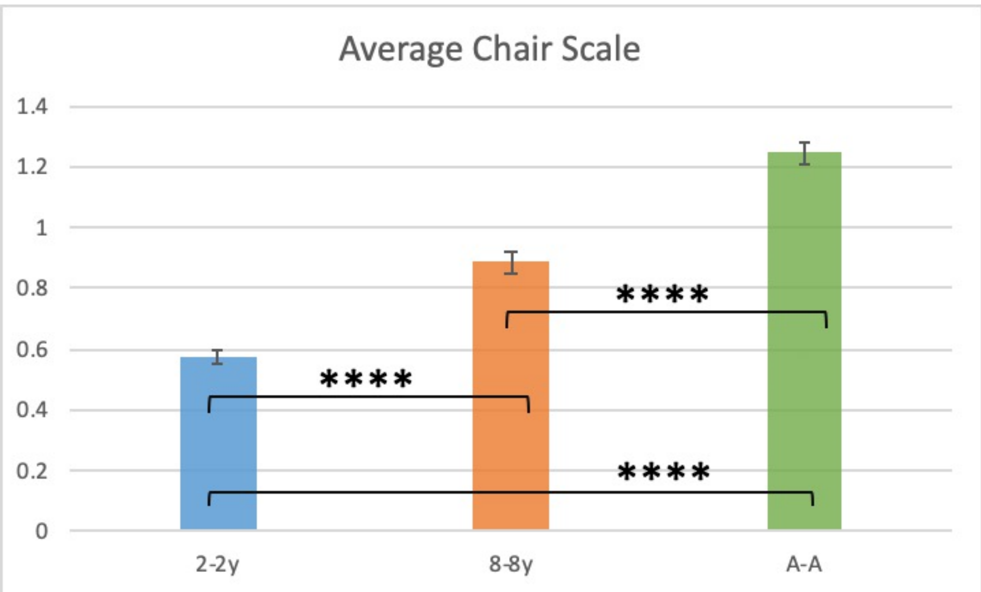

Figure 23: Average chair scale for three *Perspective Taken* (*=p<.01, **=p<.001, ***=p<.0005, ****=p<.0001).

For correlation analysis of different *Perspective Taken* and *Chair Scale,* we analysed the EH and IPD separately. The results yielded a strong positive linear relationship for both EH (r=0.912) and IPD (r=0.913), as shown in Figure 24 and 25, respectively.

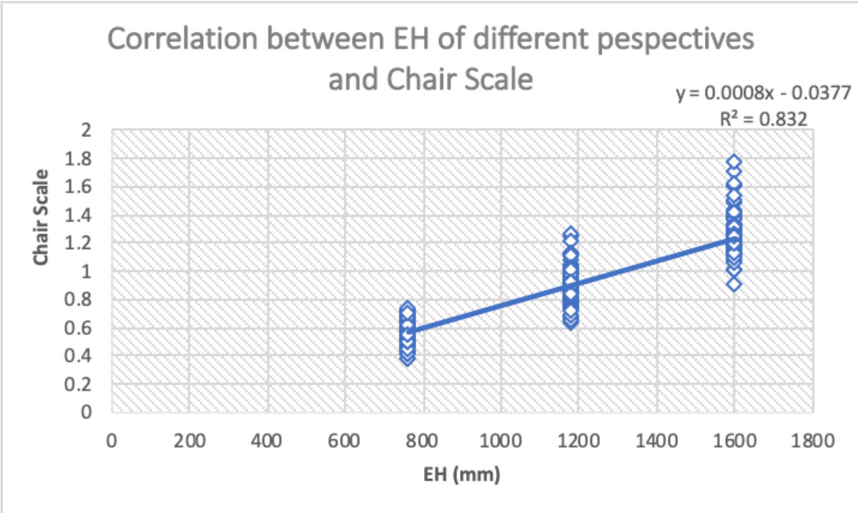

Figure 24: A correlation between EH and *Chair Scale*

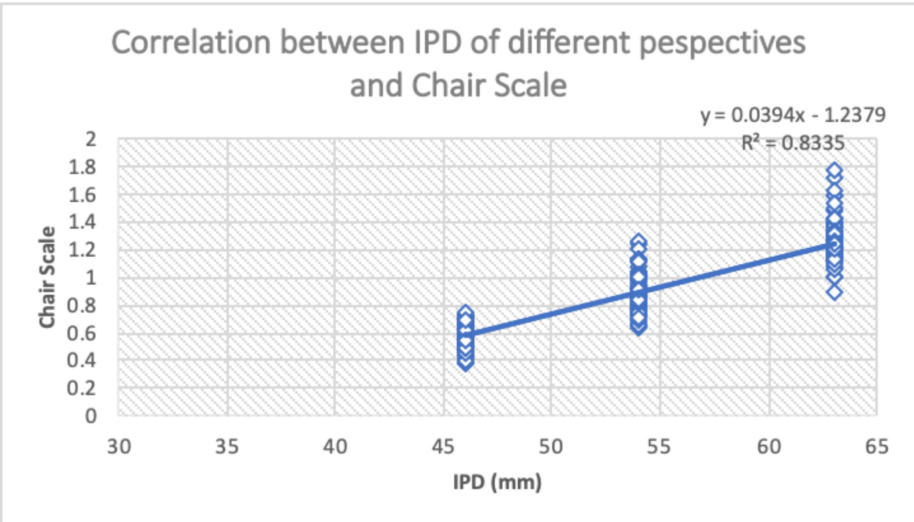

Figure 25: A correlation between IPD and *Chair Scale*

4.7 Measurements of Questionnaires

After completing the two experiments, the participants were asked to fill out three questionnaires, the system usability (SUS) questionnaire, iGroup presence questionnaire (IPQ), and the post-experiment questionnaire The results are shared in this sections.

4.7.1 System Usability Scale (SUS)

System Usability Scale (SUS) [6] is a reliable, low-cost usability scale that can be used to measure system usability. It comprises of ten statements such "I thought the system was easy to use", and "I thought there was too much inconsistency in this system". SUS uses a 5-point Likert Scale ranging from "Strongly Disagree" to "Strongly Agree". Our system was rated 69.7 on average by our participants. The average SUS score is 68, which indicates that our system is usable. However, there are rooms for improvement.

4.7.2 iGroup Presence Questionnaire (IPQ)

iGroup Presence Questionnaire (IPQ) [49] is a scale used to measure the presence experienced in a VE. It includes 14 items, one general item, and the other 13 items are divided into three subscales (Spatial Presence, Involvement and Experienced Realism). IPQ is based on a 7-point Likert Scale from "Fully Disagree" to "Fully Agree". The IPQ for our VR experience on the three subscales were: Spatial Presence ($\bar{x}$ =5.40, SD=1.40), Involvement ($\bar{x}$ =3.85, SD=1.59), Experienced Realism ($\bar{x}$ =4.15, SD=1.55). The results are shown in Figure 26.

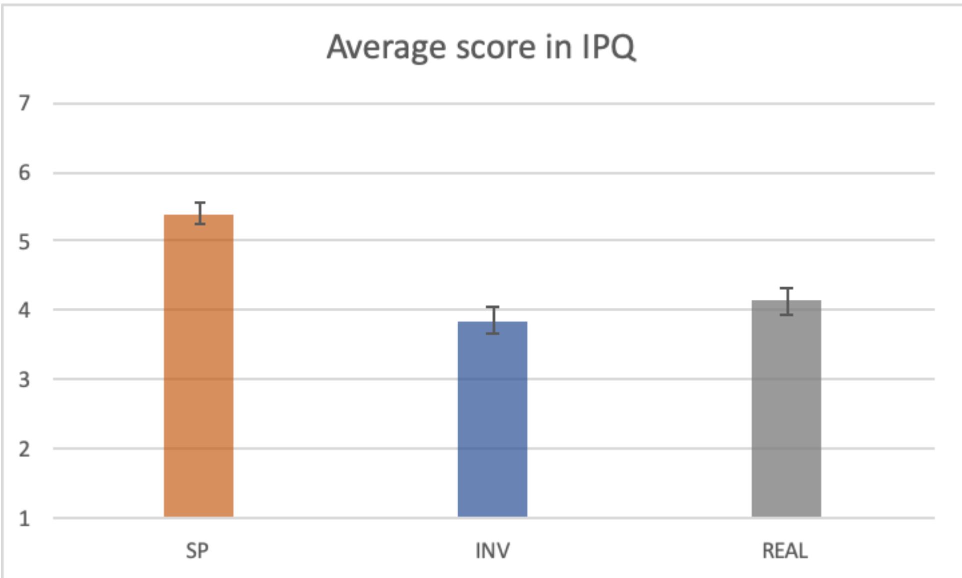

Figure 26: The average score rated for the three subscales, Spatial Presence, Involvement and Experienced Realism, of the IPQ questionnaire.

4.7.3 Post-Experiment Questionnaire

The Post-Experiment Questionnaire contained two open-ended questions as follows:

- Was there any benefit in experiencing different perspectives in the study?
- Did experiencing different perspectives influence your decision in each task?

We have gained some interesting insight from participants, which we will discuss in more detail in the next chapter in subsection 5.1.3.

Chapter 5
Discussion

In this chapter, we further discuss our findings from the user study and interpret the results of the statistical analyses. We first provide evidence to confirm or deny our hypotheses and link them back to our research questions in Section 5.1. Section 5.2 covers the limitations of our study and how they might be addressed in the follow-up research.

5.1 Answers to Hypotheses and Research Questions

We examine the outcomes of Experiment 1 and 2 in Subsection 5.1.1 and 5.1.2, respectively.

5.1.1 Experiment 1 - Risk Identification & Assessment

In this experiment, we investigated the effects of experiencing different target user perspectives on the perceived risks in VE. Our hypotheses were as follows:

Experiencing different perspectives in VE would significantly impact the participant's perception of risks in terms of:

*H1: Perceived level of risk (**Risk Rating**),*

*H2: Total number of risks identified (**Number of Risks**), and*

*H3: Average risk height found (**Risk Height**)*

Our results provided strong evidence to support all three hypotheses, *H1*, *H2*, and *H3*. It was found that experiencing different perspectives in VR had a significant impact on the participant's perception of risks in terms of the perceived level of risk (*Risk Rating*), a total number of risk identified (*Number of Risks*), and their ability to identify the risks based on average risk height (*Risk Height*).

In terms of perceived level of risk or ***Average Risk Rating***, we found that a combination of lower EH and smaller IPD influenced the participants judgement of perceived level of risk with the average ratings of *2yo* ($\bar{x}$ =3.8, SD=1.1), *8yo* ($\bar{x}$ =3.6, SD=1.2), *W/C* ($\bar{x}$ =3.2, SD=1.3), and *Adult* ($\bar{x}$ =3.1, SD=1.3). Participants found the risks more threatening from a child's perspective. This can be seen in Figure 14, where the level of risk and colours range from very low in blue, low in green, moderate in yellow, high in orange, and very high in red. It is evident that there is a higher density of blue and green dots in the *Adult* and *W/C* conditions, and more orange and red in *2yo* and *8yo* as shown in Figure 27 to 30, respectively.

In terms of number of risks identified, the ***Average Number of Risk*** were *2yo* ($\bar{x}$=19.6, SD=8.0), *8yo* ($\bar{x}$ =17.7, SD=10.8), *W/C* ($\bar{x}$ =12.4, SD=8.6), and *Adult* ($\bar{x}$ =11.6, SD=8.0). There were significantly more risks found as a child in the *2yo* and *8yo* conditions compared to an adult in *W/C* and *Adult*. Figure 31 to 34 shows the number of risks found for various intervals of height relative to the floor level, where the participants stood under different conditions: *2yo*, *8yo*, *W/C*, and *Adult*. We observe that taking a child's perspective made it easier for the participants to identify more risks in the VE given a similar amount of time in each condition. We found the participant's ability to identify the risks, in terms of ***Average Risk Height*** for *2yo* ($\bar{x}$=70.0, SD=48.8) yielded a low height level, *8yo* ($\bar{x}$ =104.2, SD=58.6) and *W/C* ($\bar{x}$ =110.4, SD=69.2) were moderate, and *Adult* ($\bar{x}$ =133.2, SD=69.8) produced a high level. This was our expectation that a unique level of height would provide a unique perspective and influence the average number of risks found.

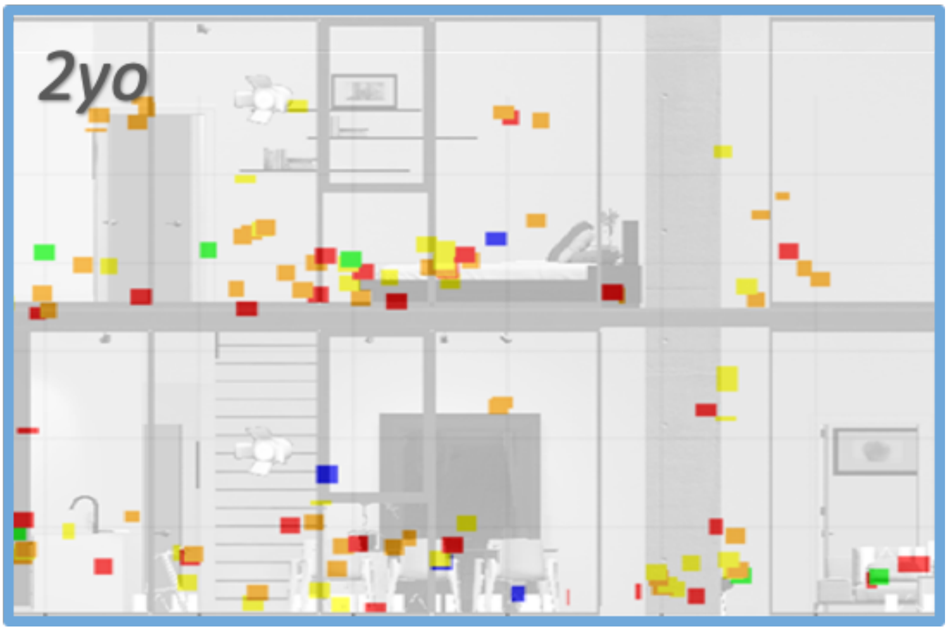

Figure 27: A partial cross-section of the two-storey apartment with the accumulated risks assessed for the *2yo* condition in Experiment 1. The Five colour dots represent the five levels of perceived risk ranging from blue- Extremely Low to red – Extremely High.

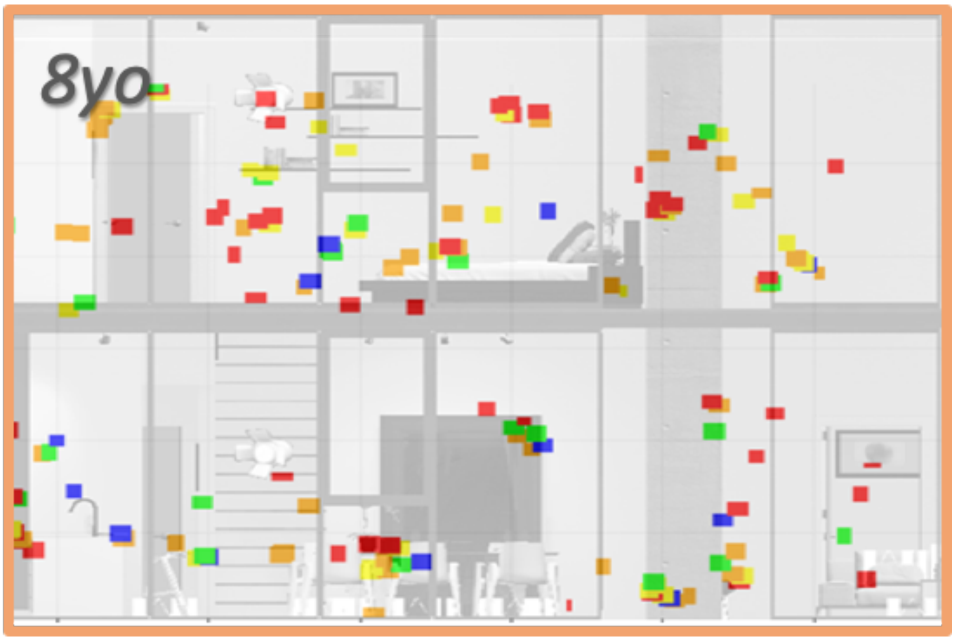

Figure 28: A partial cross-section of the two-storey apartment with the accumulated risks assessed for the 8*yo* condition in Experiment 1. The Five colour dots represent the five levels of perceived risk ranging from blue- Extremely Low to red – Extremely High.

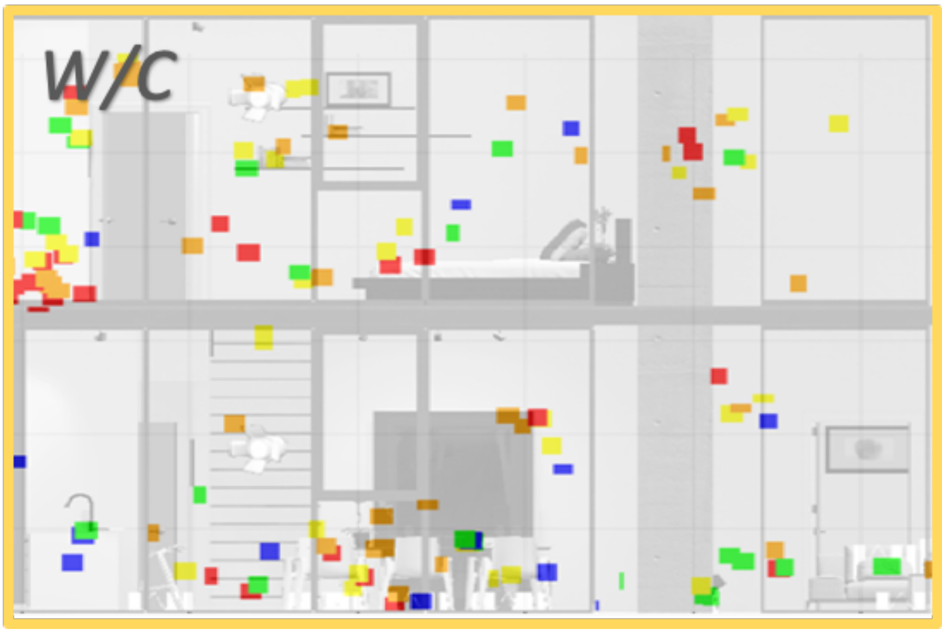

Figure 29: A partial cross-section of the two-storey apartment with the accumulated risks assessed for the *W/C* condition in Experiment 1. The Five colour dots represent the five levels of perceived risk ranging from blue-Extremely Low to red – Extremely High.

Figure 30: A partial cross-section of the two-storey apartment with the accumulated risks assessed for the *Adult* condition in Experiment 1. The Five colour dots represent the five levels of perceived risk ranging from blue-Extremely Low to red – Extremely High.

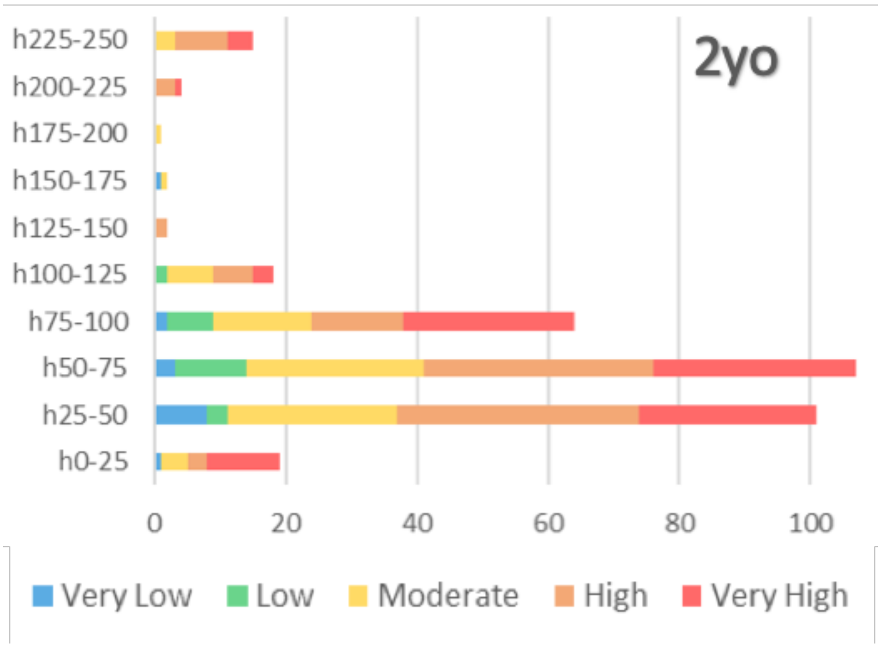

Figure 31: Plots of the number of risks recorded for all height intervals under *2yo* condition.

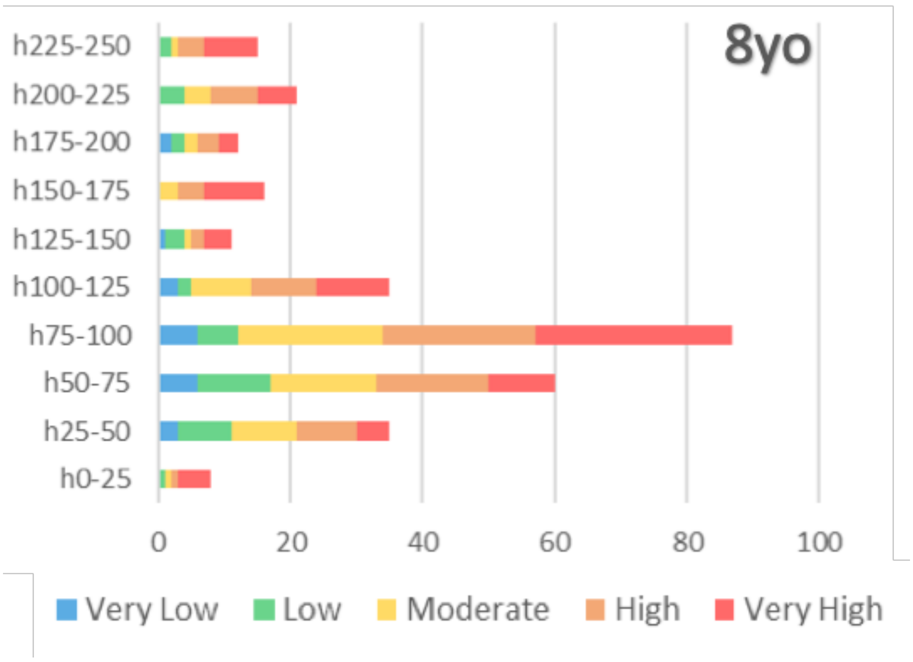

Figure 32: Plots of number of risk recorded for all height intervals under *8yo* condition.

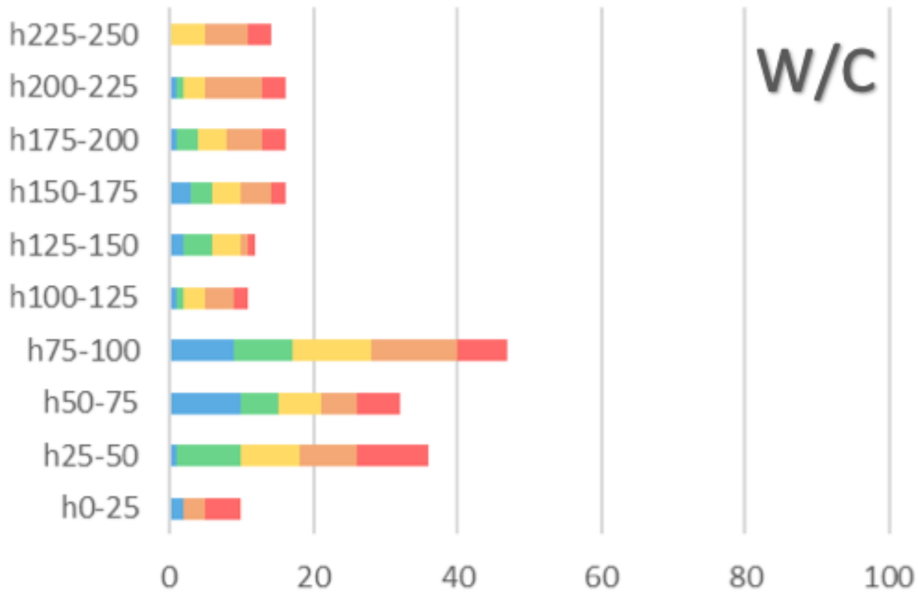

Figure 33: Plots of number of risk recorded for all height intervals under *W/C* condition.

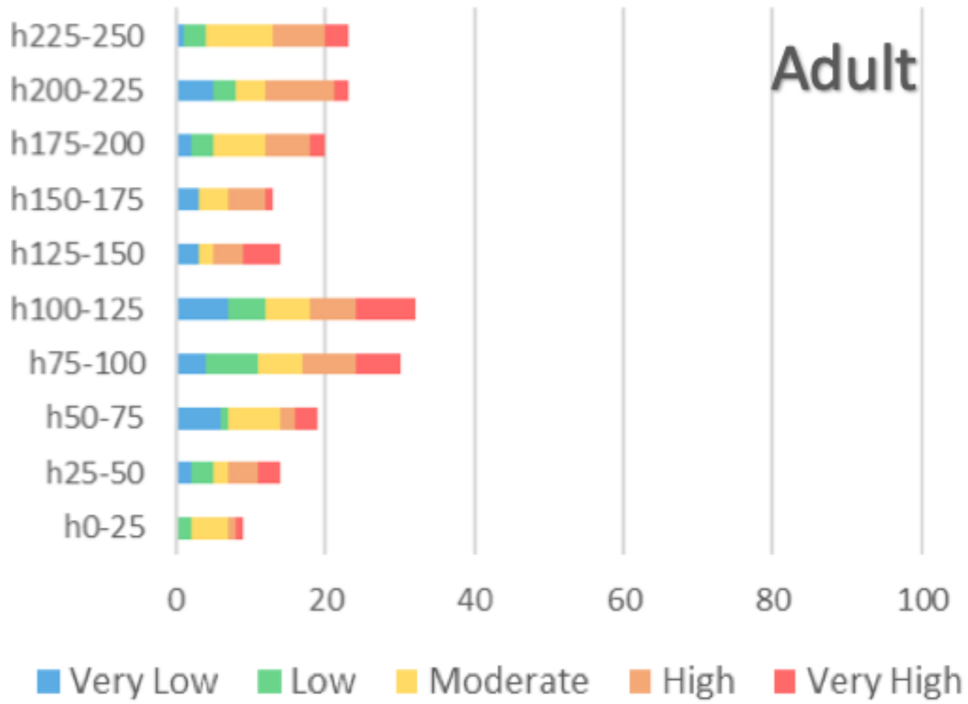

Figure 34: Plots of the number of risks recorded for all height intervals under the *Adult* condition.

5.1.2 Experiment 2 - Virtual Design Scale Estimation

For **Part A** of Experiment 2**,** we compared whether the perspective taken that matched or mismatched with the intended target user's object scale, had any impact on the estimated scale of the virtual chairs. Our results provided strong evidence to support both of our hypotheses.

*H4: The disparity between the perspective taken and target user's groups (**Target User Disparity**) would have a significant impact on the estimated scale of the virtual chair (**Chair Scale**).*

*H5: The resulting **Chair Scale** would not be significantly impacted by scaling different type of virtual chair (**Chair Type**) for the same condition.*

In terms of the *Chair Scale* of the four conditions, *2-2y* ($\bar{x}$ =0.58, SD=0.08), *A-2y* ($\bar{x}$ =0.73, SD=0.12), *A-A* ($\bar{x}$ =1.25, SD=0.15), and *2-A* ($\bar{x}$ =1.38 SD=0.31), there were significance differences between participants scaling the chair for a target user group that coincided with the perspective taken (*2-2y and A-A*) and those with the opposing perspectives (*A-2y and 2-A*). Figure 35 shows the average *Chair Scale* of the four conditions for six types of chair.

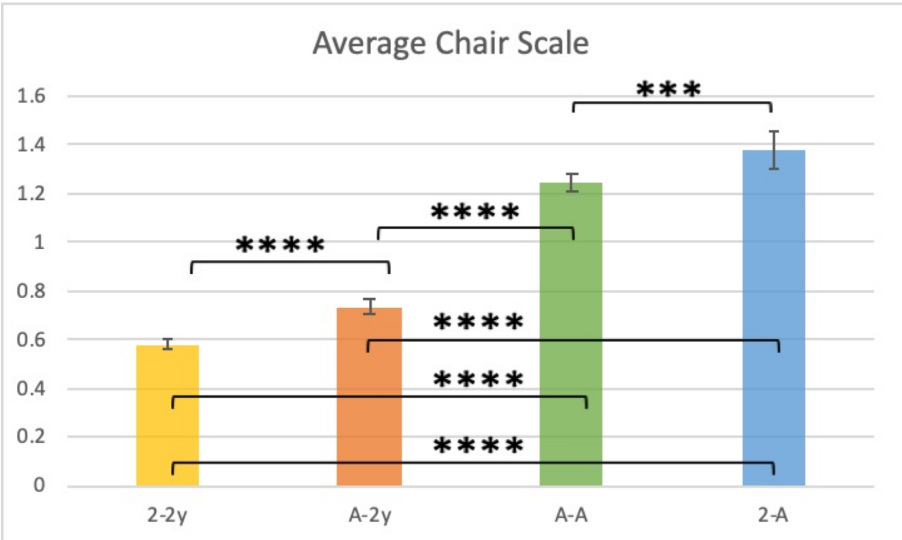

Figure 35: The average Chair Scale in the four conditions for all types of chair.

We found that when participants scaled the chair for a target user group that differed from the perspective taken, i.e. *A-2y* and *2-A*, they tended to overestimate the size of the chair. We also found that when participants scaled from a matching perspective and the target user's object scale, the resulting *Chair Scale* yielded lower variance, hence, more consistent scale.

We found no significant difference between different types of chairs, as shown in Figure 36. This finding confirmed the hypothesis, *H5*, that the *Chair*

Type of the virtual chairs did not have a significant impact on the resulting *Chair Scale* for the same *Perspective Taken*.

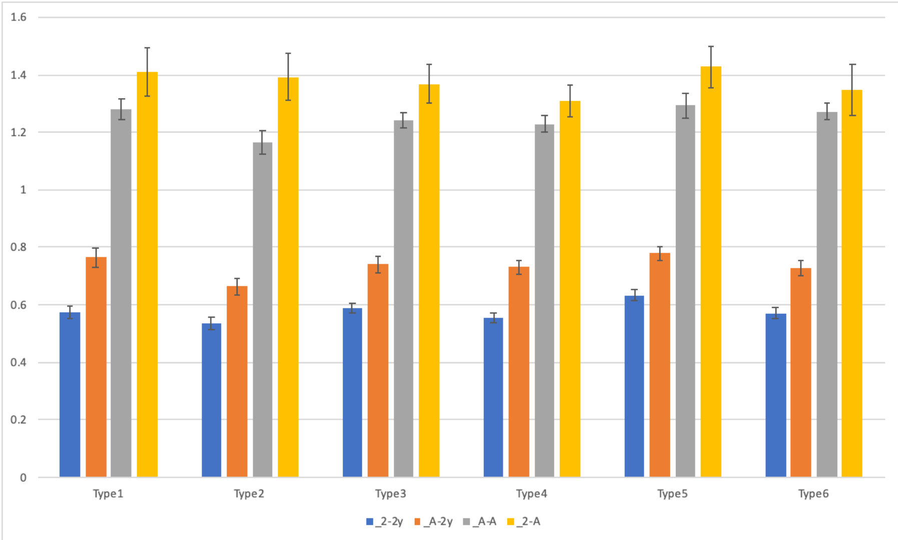

Figure 36: The average Chair Scale in the four conditions with six chair types.

Another interesting finding was that when participants experienced the virtual environment using the adult's perspective, they seemed to perceive the displayed virtual chair as smaller than it was perceived in the real world. Because the size of all virtual chairs we used in this experiment was the approximation of the chair in the real world, for an adult perspective, the default scale of 1.0 should be the size suitable for an adult to sit. However, Figure 35 shows that when participants experienced an adult perspective and scaled a chair for adults, the average *Chair Scale* was around 1.2 time the default scale. This finding aligned with past research that found users tended to underestimate objects in VR even without any embodiment for spatial reference [21].

For **Part B** in Experiment 2, we compared the three conditions of perspective taken to estimate the chair scale for the matching target user group (*2-2y*, *8-8y*, and *A-A*), our hypotheses were:

*H6: Experiencing different perspectives (**Perspective Taken**) for a matching target user group would have a significant impact on the resulting scale of the chair (**Chair Scale**).*

*H7: A **positive linear relationship** exists between the eye-height (**EH**) / interpupillary distance (**IPD**), which are the two variables of **Perspective Taken,** with the resulting Chair Scale.*

The results validated our hypothesis, *H6*, that experiencing different perspectives for a matching target user group had a significant impact on the estimated size of the virtual chair, as shown in Figure 23. Furthermore,

Figure 24 and 25 also illustrate positive correlations between EH and IPD with the resulting chair scale, respectively, confirming the hypothesis, *H7*.

5.1.3 Observations and Feedbacks

From the results of **IPQ**, our system performed well in terms of Spatial Presence. The performance of Involvement is somewhat unsatisfactory, found to be slightly lower than the average value of the scale. This might be due to the experimenter sometimes had to interfere during the task to help the participants with difficulty, which might have affected the overall immersiveness. For experienced realism, the performance of our system was average. P9 stated that she was expecting to hear ambient sounds in VE, such as wind or footsteps, which would have made the VE more realistic.

From **observation,** we found that participants showed particular interest when they experienced a *2yo* perspective during Experiment 1. Some participants showed child-like behaviours such as jumping, tiptoeing, or stretching their arms, trying to reach higher places. This aligns with the findings from past research [2, 4]. We also observed that having a child's perspective made it easier for the participants to compare their size to the environment (e.g., furniture, gaps), even though we did not provide a full-body virtual representation. We observed that most participants were able to identify structural risks quickly, e.g. sharp corners, when experiencing different perspectives, however more subtle hazards, such as chemicals, were more likely to be noticed by the participants who had children. Another finding was that participants in the *W/C* condition found it challenging to turn around and navigate in the chair, for example, in the small corridor in the VE.

In Experiment 2, we observed that participants had more difficulty scaling the chair for a target user group that mismatched to their perspective. This was especially evident in the case of experiencing a two-year-old child's perspective scaling a chair for adults, where the participants took more time adjusting the scale of the chair. In contrast, when the participants scaled for a matching perspective and target user, they were able to make decisions quickly and rarely need to readjust.

With the post-experimental questionnaire, we asked the participants two questions. For the first question "Was there any benefit in experiencing different perspectives in the study?", all participants gave a positive response. For example, P1 stated, "I didn't notice the hazards, and they didn't appear to be dangerous until I saw them from another perspective". Some participants mentioned that seeing from another perspective would help them understand the others and gain insights into the needs and threats corresponding to a different age, height, and mobility. Some participants also pointed out that experiencing different perspectives in VE might be useful for the other domains such as designing a playpen for children. P5 suggested that "People can try it in VR as a trial system before implementing any project”. P6 said that “With this kind of system, designers can eliminate the potential hazards in the environment for different people”.

For the second question “Did experiencing different perspectives influence your decision in each task?”, most participants gave positive responses, and only a single participant gave a neutral response. P6 answered “Yes, I thought more about ‘moving around and hitting something’ situation when I was in the perspective of a child of two years old. And I would consider the factor of being ‘naughty’ when I was in the perspective of a child of 8 years old”. When P16 was asked about why he gave a neutral response, he stated, “Even though the hazards stand out more when you see the environment from their perspective, what ultimately made me decide is my experience.”

5.1.4 Answers to Research Questions

In this research, we have raised three research questions, which we set out to answer. Those questions and their answers are as follows:

RQ1 – Can different levels of manipulation of eye height (EH) and interpupillary distance (IPD) be able to alter one's spatial scale perception to simulate different target groups of users?

ANS1 – The results of Experiment 1, following the discussion in Section 5.1.1, have provided strong evidence, which indicates that the manipulation of EH and IPD does alter one’s spatial scale perception and can simulate different spatial perspectives of the target groups of users.

RQ2 – Can different spatial perspectives influence one’s spatial understanding and scale estimation in design related tasks?

ANS2 – Experiment 2 as discussed in Section 5.1.2, also provides strong evidence that different spatial perspectives do influence one’s spatial understanding and their ability to estimate the scale suitable for various target groups of users in the spatial design tasks.

RQ3 – Would the experience of different perspectives influence the design decision of the designer and satisfy specific design requirements for different target groups of users?

ANS3 – The outcomes of both experiments indicate that the manipulation of one’s spatial perspective can change the way one perceived the VE and therefore influence one’s decision made in the design-related tasks.

5.2 Limitations

From the **SUS** results, we have learned that our system required further improvement. During the experiment, three users who had little VR experience felt a strong sense of dizziness when using the system. We attempted to minimise this issue by reducing the user's moving speed in VE, as the acceleration may have caused the cybersickness [51]. Furthermore, we limited our system by only support physical turning of the user's head to control the direction in VE. We also explained the participants the tricks on how to use the controller better, to reduce the effects during the training session. Nevertheless, this problem has not been solved, and it had impacts on the participant's performance in the experiment as well as their well-being.

Another limitation of the study was that there were only two professional designers of the seventeen participants. Although the general population can also benefit from the system and the target users can be anyone, professional opinions are invaluable. They can provide more in-depth insight into how our system can be used during the design process. Furthermore, they can also advise on how to improve the system and gain a better understanding of the role that the system can play in the actual design process.

Chapter 6
Conclusion and Future Work

6.1 Conclusion

We presented a multi-scale VR system and a user study comprised of two experiments to investigate multiple levels of manipulation of spatial scale perception for two design-related tasks. They were risk assessment in interior design and scale estimation of virtual chairs. In the first experiment, four unique perspectives; a two-year-old child, eight-year-old child, an adult in a wheelchair, and an adult, were compared in terms of the perceived level of risk, the number of risks identified, and average risk height. The results yielded strong evidence that experiencing different perspectives in VR significantly impact the participant's perception of risks.

In the second experiment, participants experienced three perspectives (two-year-old child, eight-year-old child, and an adult) for scaling six types of virtual chairs. Apart from scaling for the perspective taken, the participants as a two-year-old child had to scale the chairs for adults, and vice versa. Two objectives were used to compare different conditions. First, we compared four conditions between the perspective taken and the target user disparity. The results showed that experiencing the same or different perspective taken from the target user group had a significant impact on the estimated scale of the chairs. Second, we compared three matching perspectives to the target user group. We found that different perspectives also had a significant impact on the scale estimation with a strong positive correlation between EH and IPD to the resulting scale.

From the findings, we strongly believe that we have fulfiled our research goals. We implemented a VR system that enabled users to experience VE through different perspectives by manipulating their virtual EH and IPD. With this VR system, we investigated the different levels of manipulation of EH and IPD to provide different spatial scale perception of multiple target groups of users and therefore fulfilled our first research goal. Next, we examined different perspectives for scale estimation to better understand the appropriate perspectives to enable a suitable estimation of the virtual object scale for the target groups of users, and this was our second goal. Finally, we found that by experiencing different perspectives, the participants were able to empathise with the target users, which was our third goal, to utilise different perspectives for assisting the designers in meeting the needs of different target groups of users.

6.2 Future work

Most participants were able to identify structural risks (such as sharp corners) when experiencing child-like perspectives. Nevertheless, participants who had their own children were more likely to notice less inherent risks such as chemical hazard. For future work, we would like to identify further the types of risks that are more effective to visualise and to identify through the manipulation of spatial scaled perception with more specific scenarios and groups of participants based on their occupation. For example, we can investigate a scenario around a warehouse and so we would focus on recruiting warehouse workers. To improve the user experience, we would like to improve the system in two areas. First is to reduce the cybersickness, which is the current limitation of our locomotion technique. We are considering using redirected walking if space permits., Second is to enhance the realism of the VE by adding interactivity and ambient sound.

References

[1] Parastoo Abtahi, Mar Gonzalez-Franco, Eyal Ofek, and Anthony Steed, 2019. I'm a Giant: Walking in Large Virtual Environments at High Speed Gains. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* ACM, 522.

[2] Sun Joo Ahn, Joshua Bostick, Elise Ogle, Kristine L Nowak, Kara T Mcgillicuddy, and Jeremy N Bailenson, 2016. Experiencing nature: Embodying animals in immersive virtual environments increases inclusion of nature in self and involvement with nature. *Journal of Computer-Mediated Communication 21*, 6, 399-419.

[3] Nomana Anjum, Jeanette Paul, and Roland Ashcroft, 2005. The changing environment of offices: A challenge for furniture design. *Design Studies 26*, 1, 73-95.

[4] Domna Banakou, Raphaela Groten, and Mel Slater, 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences 110*, 31, 12846-12851.

[5] Scot Best, 1996. Perceptual and oculomotor implications of interpupillary distance settings on a head-mounted virtual display. In *Proceedings of the IEEE 1996 National Aerospace and Electronics Conference NAECON 1996* IEEE, 429-434.

[6] John Brooke, 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry 189*, 194, 4-7.

[7] John Coles and Naomi House, 2007. *The fundamentals of interior architecture*. AVA Publishing.

[8] Carolina Cruz-Neira, Daniel J Sandin, and Thomas A Defanti, 1993. Surround-screen projection-based virtual reality: the design and implementation of the CAVE. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, 135-142.

[9] Özgen Osman Demirbaş, 2001. The relation of learning styles and performance scores of the students in interior architecture education Bilkent University.

[10] Melissa W. Dixon, Maryjane Wraga, Dennis R. Proffitt, and George C. Williams, 2000. Eye height scaling of absolute size in immersive and nonimmersive displays. *Journal of Experimental Psychology: Human Perception and Performance 26*, 2, 582-593. DOI= http://dx.doi.org/10.1037/0096-1523.26.2.582.

[11] Neil A Dodgson, 2004. Variation and extrema of human interpupillary distance. In *Stereoscopic Displays and Virtual Reality Systems XI* International Society for Optics and Photonics, 36-46.

[12] Tyrone Donnon, Jean-Gaston Descôteaux, and Claudio Violato, 2005. Impact of cognitive imaging and sex differences on the development of laparoscopic suturing skills. *Canadian journal of surgery 48*, 5, 387.
[13] Tatjana Filipović, 2003. Changes in the interpupillary distance (IPD) with ages and its effect on the near convergence/distance (NC/D) ratio. *Collegium antropologicum 27*, 2, 723-727.
[14] Cédric Fleury, Alain Chauffaut, Thierry Duval, Valérie Gouranton, and Bruno Arnaldi, 2010. A generic model for embedding users' physical workspaces into multi-scale collaborative virtual environments.
[15] Bhw Hadikusumo and Steve Rowlinson, 2002. Integration of virtually real construction model and design-for-safety-process database. *Automation in construction 11*, 5, 501-509.
[16] Daniel Henry and Tom Furness, 1993. Spatial perception in virtual environments: Evaluating an architectural application. In *Proceedings of IEEE Virtual Reality Annual International Symposium* IEEE, 33-40.
[17] Fernanda Herrera, Jeremy Bailenson, Erika Weisz, Elise Ogle, and Jamil Zaki, 2018. Building long-term empathy: A large-scale comparison of traditional and virtual reality perspective-taking. *PloS one 13*, 10, e0204494.
[18] Eunice Jun, Jeanine K. Stefanucci, Sarah H. Creem-Regehr, Michael N. Geuss, and William B. Thompson, 2015. Big Foot: Using the Size of a Virtual Foot to Scale Gap Width. *ACM Trans. Appl. Percept. 12*, 4, 1-12. DOI= http://dx.doi.org/10.1145/2811266.
[19] Youjiin Jurng and Su-Jeong Hwang, 2010. Policy Standards for Children's Furniture in Environmental Design. *Policy & The Environment*, 68.
[20] Michael D Keall, Michael Baker, Philippa Howden-Chapman, and Malcolm Cunningham, 2008. Association between the number of home injury hazards and home injury. *Accident Analysis & Prevention 40*, 3, 887-893.
[21] Jeanine K Stefanucci, Sarah H Creem-Regehr, William B Thompson, David A Lessard, and Michael N Geuss, 2015. Evaluating the accuracy of size perception on screen-based displays: Displayed objects appear smaller than real objects. *Journal of Experimental Psychology: Applied 21*, 3, 215.
[22] Jangyoon Kim and Victoria Interrante, 2017. Dwarf or giant: the influence of interpupillary distance and eye height on size perception in virtual environments. In *Proceedings of the Proceedings of the 27th International Conference on Artificial Reality and Telexistence and 22nd Eurographics Symposium on Virtual Environments* (Adelaide, Australia2017), Eurographics Association, 3298859, 153-160.
[23] Regis Kopper, Tao Ni, Doug A Bowman, and Marcio Pinho, 2006. Design and evaluation of navigation techniques for multiscale virtual

environments. In *Ieee virtual reality conference (vr 2006)* Ieee, 175-182.
[24] Andrey Krekhov, Sebastian Cmentowski, Katharina Emmerich, Maic Masuch, and Jens Krüger, 2018. GulliVR: A walking-oriented technique for navigation in virtual reality games based on virtual body resizing. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play* ACM, 243-256.
[25] Robert J Kuczmarski, 2000. CDC growth charts; United States.
[26] Morgan Le Chénéchal, Jérémy Lacoche, Jérôme Royan, Thierry Duval, Valérie Gouranton, and Bruno Arnaldi, 2016. When the giant meets the ant an asymmetric approach for collaborative and concurrent object manipulation in a multi-scale environment. In *2016 IEEE Third VR International Workshop on Collaborative Virtual Environments (3DCVE)* IEEE, 18-22.
[27] Markus Leyrer, Sally A. Linkenauger, Heinrich H. B, #252, Lthoff, Uwe Kloos, and Betty Mohler, 2011. The influence of eye height and avatars on egocentric distance estimates in immersive virtual environments. In *Proceedings of the Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization* (Toulouse, France2011), ACM, 2077464, 67-74. DOI= http://dx.doi.org/10.1145/2077451.2077464.
[28] Sally A Linkenauger, Heinrich H Bülthoff, and Betty J Mohler, 2015. Virtual arm′ s reach influences perceived distances but only after experience reaching. *Neuropsychologia 70*, 393-401.
[29] Sally A Linkenauger, Markus Leyrer, Heinrich H Bülthoff, and Betty J Mohler, 2013. Welcome to wonderland: The influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. *PloS one 8*, 7, e68594.
[30] Wt Lo and Richard Hy So, 2001. Cybersickness in the presence of scene rotational movements along different axes. *Applied ergonomics 32*, 1, 1-14.
[31] Cognifit Ltd., 2020. Spatial Perception Cognitive Ability CogniFit Ltd., cognifit.com.
[32] Colleen Maclachlan and Howard C Howland, 2002. Normal values and standard deviations for pupil diameter and interpupillary distance in subjects aged 1 month to 19 years. *Ophthalmic and Physiological Optics 22*, 3, 175-182.
[33] Lara Maister, Mel Slater, Maria V Sanchez-Vives, and Manos Tsakiris, 2015. Changing bodies changes minds: owning another body affects social cognition. *Trends in cognitive sciences 19*, 1, 6-12.
[34] Dragana Nikolic and Ben Windess. Evaluating immersive and non-immersive VR for spatial understanding in undergraduate construction education.

[35] Jun Nishida, Soichiro Matsuda, Mika Oki, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki, 2019. Egocentric Smaller-person Experience through a Change in Visual Perspective. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* ACM, 696.

[36] Nami Ogawa, Takuji Narumi, and Michitaka Hirose, 2017. Distortion in perceived size and body-based scaling in virtual environments. In *Proceedings of the 8th Augmented Human International Conference*, 1-5.

[37] Kimberley Osberg, 1997. Spatial cognition in the virtual environment.

[38] Tabitha C Peck, Sofia Seinfeld, Salvatore M Aglioti, and Mel Slater, 2013. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and cognition 22*, 3, 779-787.

[39] David L Penn, James D Ivory, and Abigail Judge, 2010. The virtual doppelganger: Effects of a virtual reality simulator on perceptions of schizophrenia. *The Journal of nervous and mental disease 198*, 6, 437-443.

[40] Amotz Perlman, Rafael Sacks, and Ronen Barak, 2014. Hazard recognition and risk perception in construction. *Safety science 64*, 22-31.

[41] Celine Pinet, 1997. Design evaluation based on virtual representation of spaces.

[42] Thammathip Piumsomboon, Arindam Day, Barrett Ens, Youngho Lee, Gun Lee, and Mark Billinghurst, 2017. Exploring enhancements for remote mixed reality collaboration. In *SIGGRAPH Asia 2017 Mobile Graphics & Interactive Applications* ACM, 16.

[43] Thammathip Piumsomboon, Gun A Lee, Barrett Ens, Bruce H Thomas, and Mark Billinghurst, 2018. Superman vs giant: a study on spatial perception for a multi-scale mixed reality flying telepresence interface. *IEEE transactions on visualization and computer graphics 24*, 11, 2974-2982.

[44] Thammathip Piumsomboon, Gun A Lee, Jonathon D Hart, Barrett Ens, Robert W Lindeman, Bruce H Thomas, and Mark Billinghurst, 2018. Mini-me: an adaptive avatar for mixed reality remote collaboration. In *Proceedings of the 2018 CHI conference on human factors in computing systems* ACM, 46.

[45] Thammathip Piumsomboon, Gun A Lee, Andrew Irlitti, Barrett Ens, Bruce H Thomas, and Mark Billinghurst, 2019. On the shoulder of the giant: A multi-scale mixed reality collaboration with 360 video sharing and tangible interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1-17.

[46] Jayne Pivik, Joan Mccomas, Ian Macfarlane, and Marc Laflamme, 2002. Using virtual reality to teach disability awareness. *Journal of Educational Computing Research 26*, 2, 203-218.

[47] Helen B Pryor, 1969. Objective measurement of interpupillary distance. *Pediatrics 44*, 6, 973-977.
[48] Rafael Sacks, Jennifer Whyte, Dana Swissa, Gabriel Raviv, Wei Zhou, and Aviad Shapira, 2015. Safety by design: dialogues between designers and builders using virtual reality. *Construction Management and Economics 33*, 1, 55-72.
[49] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht, 2001. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments 10*, 3, 266-281.
[50] Alison Simmons, 2003. Spatial perception from a Cartesian point of view. *Philosophical Topics 31*, 1/2, 395-423.
[51] Richard Hy So, Andy Ho, and Wt Lo, 2001. A metric to quantify virtual scene movement for the study of cybersickness: Definition, implementation, and verification. *Presence: Teleoperators & Virtual Environments 10*, 2, 193-215.
[52] Margaret Stevens, C D'arcy J Holman, and Nicole Bennett, 2001. Preventing falls in older people: impact of an intervention to reduce environmental hazards in the home. *Journal of the American Geriatrics Society 49*, 11, 1442-1447.
[53] Ana Tajadura-Jiménez, Domna Banakou, Nadia Bianchi-Berthouze, and Mel Slater, 2017. Embodiment in a child-like talking virtual body influences object size perception, self-identification, and subsequent real speaking. *Scientific reports 7*, 1, 9637.
[54] Peter Willemsen, Amy A Gooch, William B Thompson, and Sarah H Creem-Regehr, 2008. Effects of stereo viewing conditions on distance perception in virtual environments. *Presence: Teleoperators and Virtual Environments 17*, 1, 91-101.
[55] Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins, 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI conference on human factors in computing systems*, 143-146.
[56] Nick Yee and Jeremy Bailenson, 2007. The Proteus effect: The effect of transformed self-representation on behavior. *Human communication research 33*, 3, 271-290.
[57] Nick Yee and Jeremy N Bailenson, 2006. Walk a mile in digital shoes: The impact of embodied perspective-taking on the reduction of negative stereotyping in immersive virtual environments. *Proceedings of PRESENCE 24*, 26.
[58] Xiaolong Zhang and George W. Furnas, 2005. mCVEs: Using Cross-Scale Collaboration to Support User Interaction with Multiscale Structures. *Presence: Teleoperators & Virtual Environments 14*, 1, 31-46. DOI= http://dx.doi.org/10.1162/1054746053890288.

Appendix

Appendix A

Information Sheet, Consent Form and Advertisement

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department: HIT Lab NZ
Telephone: +64 (0)21 208 7789
Email: jingjing.zhang@pg.canterbury.ac.nz
16 October 2019

Spatial Scale Perception in Immersive Virtual Environments Research
Information Sheet for Participants

This study explores the effects of spatial scale perception in immersive virtual reality. The goal of this study is to investigate a virtual reality (VR) system that supports multiple spatially-scaled perspectives to assist users in an application of interior design for two design related tasks. In the first task, the participants will assess potential risks of an interior design in a virtual two-story apartment. In the second task, the participants are required to scale six virtual chairs to the preferable size for target age groups from three scaled perspective.

If you choose to participate this study, you acknowledge that you are at least 18 years old. If you have abnormal vision, balance issues, and/or epilepsy, you are not eligible to participate the experiment.

If you choose to take part in this study, your involvement in this project will be:

- You will start with an introductory session (5 min) to get an understanding about the purpose of the experiment, devices and controls, objects and settings, tasks, the right of cancellation, camera recording purposes, potential risks and procedures, recommendations for safety, and filling in and signing the consent forms.
- After completing the consent forms, the researcher will give you a set of pre-experiment questionnaires to fill out.
- After that, you will perform the first part with four conditions. In each condition, you will go through the following steps:
  - A brief training session (1 min).
  - Risk and hazard identification task (20 min).
  - After each condition, there will be a 1-2 minute break.
- For the second part, you will perform five conditions. In each condition, you will go through the following steps:
  - A brief training session (1 min).
  - Scaling virtual chairs task (10 min).
  - Filling in post-study questionnaires (5 min).
- In the end, an appreciation form and $10 Westfield voucher will be given to you as an acknowledgement of your contribution to the project.
- If you are feeling unwell, you should not drive or operate heavy machinery for two hours after this experiment.

While performing VR tasks, there is a risk of feeling nauseous or cybersickness. If you feel it is difficult for you to continue, you can sit down and relax on the couch until you feel comfortable enough. In the worst-case scenario, if you cannot keep performing at all or have unforeseen behaviour, the researcher will terminate your experimental session and escort you to UC Health Centre. However, the likelihood of this happening is very small. You can decide to stop and leave this experiment at any point in time.

Participation is voluntary and you have the right to withdraw at any stage without penalty. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, any information relating to you will be removed, however, once analysis of raw data starts on 1 December 2019, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published for future use beyond the master thesis, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality all the data will be stored securely and only the researchers mentioned on the consent form will have access to it. However, we might also share parts of the raw anonymized data with other researchers if there is a need to do so. The data will be kept securely stored for a minimum period of five years on storage systems within the University of Canterbury, and securely destroyed after that.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out by Jingjing Zhang (jingjing.zhang@pg.canterbury.ac.nz) under the supervision of Dr. Tham Piumsomboon, who can be contacted at tham.piumsomboon@canterbury.ac.nz. They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and give it to the test moderator.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Department: HIT Lab NZ
Telephone: +64 (0)21 208 7789
Email: *jingjing.zhang@pg.canterbury.ac.nz*
16 October 2019

Spatial Scale Perception in Immersive Virtual Environments
Research Information Sheet for Participants

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher Jingjing Zhang and the supervisor Dr. Tham Piumsomboon, and that any published or reported results will not identify me. I understand that a thesis is a public document and will be available through the UC Library.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after five years.
- ☐ I understand that parts of the anonymized data could be shared with other researchers beyond this research if there is a need to do so in the future (e.g., related development, teaching or research).
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher [Jingjing Zhang, jingjing.zhang@pg.canterbury.ac.nz] or supervisors [Dr. Tham Piumsomboon, tham.piumsomboon@canterbury.ac.nz] for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I would like a summary of the results of the project.
- ☐ By signing below, I agree to participate in this research project.

Name:____________________Signed:________________Date:__________________

Email address *(for report of findings, if applicable):*


From 1st December to 1st January
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND
HITLabNZ
www.hitlabnz.org
You will have a chance to:
explore a virtual two-storey apartment with multiple spatial scaled perspective
participate in a 1 hour long experiment
receive a $10 Westfield voucher
CONTACT INFORMATION
jingjing.zhang@pg.canterbury.ac.nz
John Britten Building, Level 2
HIT Lab NZ, University of Canterbury
VOLUNTEERS NEEDED FOR A VIRTUAL REALITY STUDY

Appendix B

Questionnaires

*Participant number*_____

UC UNIVERSITY OF CANTERBURY Te Whare Wānanga o Waitaha CHRISTCHURCH NEW ZEALAND
HITLabNZ Human Interface Technology Lab New Zealand Hangarau Tangata, Tangata Hangarau www.hitlabnz.org

Pre-Experiment Questionnaire

1. Age: ____
2. Height (cm): ____
3. Gender:
   - o Female
   - o Male
   - o Other
   - o Choose not to answer
4. Do you have any children?
   - o Yes
   - o No
   - o Choose not to answer
5. Have you used a VR headset before?
   - o Never
   - o A few times a year
   - o A few times a month
   - o A few times a week
   - o Daily

*Participant number*_____

*Condition*___

System Usability Scale

Rate the following based on how much you agree with the given statement

Strongly Disagree — Strongly agree

Statements	1	2	3	4	5
I think that I would like to use this system frequently.					
I found the system unnecessarily complex.					
I thought the system was easy to use.					
I think that I would need the support of a technical person to be able to use this system.					
I found the various functions in this system were well integrated.					
I thought there was too much inconsistency in this system.					
I would imagine that most people would learn to use this system very quickly.					
I found the system very cumbersome to use.					
I felt very confident using the system.					
I needed to learn a lot of things before I could get going with this system.					

*Participant number*_____

*Condition*___

IPQ questionnaire

Q1. In the computer generated world, I had a sense of "being there".
Not at all ○ ○ ○ ○ ○ ○ ○ very much

Q2. Somehow I felt that the virtual world surrounded me.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q3. I felt like I was just perceiving pictures.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q4. I did not feel present in the virtual space.
Did not feel ○ ○ ○ ○ ○ ○ ○ felt present

Q5. I had a sense of acting in the virtual space, rather than operating something from outside.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q6. I felt present in the virtual space.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q7. How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?
Extremely aware ○ ○ ○ ○ ○ ○ ○ not aware at all

Q8. I was not aware of my real environment.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q9. I still paid attention to the real environment.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q10. I was completely captivated by the virtual world.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Q11. How real did the virtual world seem to you?
Completely real ○ ○ ○ ○ ○ ○ ○ not real at all

Q12. How much did your experience in the virtual environment seem consistent with your real world experience?
Not consistent ○ ○ ○ ○ ○ ○ ○ very consistent

Q13. How real did the virtual world seem to you?
About as real as an imagined world ○ ○ ○ ○ ○ ○ ○ indistinguishable from the real world

Q14. The virtual world seemed more realistic than the real world.
Fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

Post-Experiment Questionnaire

1) **Was there any benefit in experiencing different perspectives in the study? Please explain and give some examples.**

2) **Did experiencing different perspectives influence your decision in each task?**